STUDIES ON CERTAIN ASPECTS OF SEMI-FLUIDIZATION

BY

GOPENDRA KISHORE ROY

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GOPENDRA KISHORE ROY

B.Sc. Chem. Engg., Banares Hindu University, 1966.

M.Tech. Chem. Engg., Indian Institute of Technology, Kharagpur, 1971.

Aassociate Member, Institute of Engineers (India) and Indian Institute of Chemical Engineers.

Lecturer in the Department of Chemical Engineering, Regional Engineering College, Rourkela since October 1966.

C O N T E N T S

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A thesis entitled " Studies on Certain Aspects of Semi-fluidization" is submitted herewith. This is the first thesis based on the work planned to be carried **out** since 1968 on semi-fluidization- a new method of solid - fluid contacting visualized in the early 1960's. This work has been initiated in the department of Chemical Engineering and overcoming considerable initial troubles, the results obtained have been codified in the form of this Doctoral the sis .

In the present work, two sets of apparatus have been constructed and experimental data have been obtained on the various aspects like the prediction of minimum and maximum semi-fluidization velocities, packed bed formation and total pressure drop in the semifluidized bed. These will form the basis for the design of semifluidized bed reactors for carrying out fast exothermic reactions with better control.

The data have been correlated by means of dimensionless groups. The experimental values have been compared with those obtained, using correlations.

Gopendra Kishore Roy
(Gopendra Kishore Roy) 15th. Aug 74

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Altogether 115 sets of runs have been taken for liquid-solid systems. Four different non-spherical materials viz., dolomite, chromite, baryte and iron ore of size 14/16 BSS and 36/44 BSS have been studied. In addition, three more sizes like 6/8, 25/30 and 52/60 BSS have been studied for dolomite only. The lowest and highest densities of solids used are 2.83 and 5.25 gm./cc. respectively.

In case of gas-solid systems, 47 sets of runs have been taken. Dolomite of four different sizes (6/8, 14/16, 25/30 and 36/44 BSS) and chromite, baryte and iron ore of one size (14/16 BSS) have been used in the investigations.

Following correlations have been developed. For maximum semi-fluidization velocity the equation is -

$$G_{msf} = 1.85 \times 10^4 \; \frac{(d_p)^{0.65} \left[\rho_f \, (\rho_s - \rho_f) \right]^{0.55}}{\mu^{0.10}} \qquad \ldots(1.A)$$

for liquid-solid systems, and

$$G_{msf} = 1.37 \times 10^4 \; \frac{(d_p)^{0.65} \left[\rho_f \, (\rho_s - \rho_f) \right]^{0.55}}{\mu^{0.10}} \qquad \ldots(1.B)$$

for gas-solid systems.

Where, G_{msf} = mass velocity of fluid required for maximum semi-fluidization condition

d_p = average diameter of the particle

ρ_f = density of fluid

ρ_s = density of solid

μ = viscosity of the fluid.

For minimum semi-fluidization velocity the equation reads as -

$$\frac{G_{osf}}{G_{msf}} = 0.473 \left(\frac{D_c}{d_p}\right)^{-0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38} \qquad \ldots \qquad (2.A)$$

for liquid-solid systems, and

$$\frac{G_{osf}}{G_{msf}} = 0.071 \left(\frac{D_c}{d_p}\right)^{-0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38} \qquad \ldots \qquad (2.B)$$

for gas-solid systems.

Where, G_{osf} = mass velocity of fluid required for minimum semi-fluidization condition

D_c = diameter of the semifluidizer

R = bed expansion ratio in semi-fluidization (explained subsequently)

The above equations are of very general nature with only the change in the numerical coefficients for the two systems.

In Chapter-VI, the investigations relating to the relative distribution of particles in the packed and fluidized sections of a semifluidized bed, are incorporated.

A correlation has been developed for the prediction of packed bed in terms of semi-fluidization velocity ratio and other dimensionless groups of the system. The correlation is -

$$\frac{G_{sf}}{G_{msf}} = 0.925 \left(\frac{D_c}{d_p}\right)^{-0.15} \left(\frac{\rho_s}{\rho_f}\right)^{-0.12} (R)^{0.43} \left(\frac{h_{pa}}{h_s}\right)^{0.32} \qquad \ldots (3.A)$$

for liquid-solid systems, and

$$\frac{G_{sf}}{G_{msf}} = 4.80 \left(\frac{D_c}{d_p}\right)^{-0.18} \left(\frac{\rho_s}{\rho_f}\right)^{-0.32} (R)^{0.81} \left(\frac{h_{pa}}{h_s}\right)^{0.59} \quad ..(3.B)$$

for gas-solid systems.

Where, G_{sf} = mass velocity of fluid required for semi-fluidization condition

h_{pa} = height of packed bed in semi-fluidization

h_s = initial static bed height before experiment.

Chapter-VII, deals with the prediction of pressure drop in liquid-solid and gas-solid semifluidized beds. Based on experimental data, correlations have been developed in terms of various system parameters for the above cases. These are -

$$\frac{\Delta P_T}{\Delta P_{osf}} = 19.50 \left(\frac{D_c}{d_p}\right)^{-0.17} \left(\frac{\rho_s}{\rho_f}\right)^{0.48} (R)^{0.28} \left(\frac{h_{pa}}{h_s}\right)^{0.89} \quad ..(4.A)$$

for liquid-solid systems, and

$$\frac{\Delta P_T}{\Delta P_{osf}} = 0.22 \left(\frac{D_c}{d_p}\right)^{-0.21} \left(\frac{\rho_s}{\rho_f}\right)^{0.43} (R)^{1.71} \left(\frac{h_{pa}}{h_s}\right)^{1.24} \quad ..(4.B)$$

for gas-solid systems.

Where, ΔP_T = pressure drop across semifluidized bed

ΔP_{osf} = pressure drop of the bed corresponding to the onset of semi-fluidization.

In Appendix- A, the calibration data for the rotameters and orifice meters used in both the systems are given. The variation of pressure drop through the restraint with fluid mass velocity has also been included for the gas- solid system.

Appendix- B, contains the experimental data relating to the dynamic studies for liquid- solid and gas- solid semi-fluidization.

A few reprints of the published papers by the author, relating to semi-fluidization and other relevant fields of chemical engineering have been incorporated in Appendix- C.

C H A P T E R - I

INTRODUCTION

INTRODUCTION

It can be seen from published information that the fluidization technique was adopted in the middle of the nineteenth century. It hit the industrial scene in a big way in 1942 with catalytic cracking and has since moved to many other areas. It appears that the ideas are suffi - ciently clear now and tools are developed for design purposes. In addition to the number of research papers, six books have been published on the subject. This technique is acclaimed to be one of the most versatile solid-fluid contacting methods.

At this juncture just about a decade back, Fan, Yang and Wen visualised a new method of solid- fluid contacting in which a section of the bed will be in fluidized state whereas the remaining will behave as a fixed bed. This they have named as "Semi-fluidization". This technique overcomes the drawbacks of the packed and the fluidized beds and hence can act as a compromise between the two.

More than about twenty research papers have been published by different researchers on various aspects of this technique such as dynamics, heat transfer and mass transfer. Though the application of semi-fluidization has been specifically recommended for use in industrial reactors, there seems to be no published information so far.

While the following areas, like,

(i) prediction of the onset and the maximum semi-fluidization velocities,

(ii) prediction of packed bed formation, and

(iii) prediction of pressure drop in a semi-fluidized bed

have been widely studied, these have been restricted to the close-cut fractions of irregular solids and smaller diameters of fluidizing columns.

The effects of mixed particle sizes, particle shape, surface active agents on the fluidizing media, the restraint geometry are some of the areas, which have not been explored yet.

Even though the semi-fluidization phenomenon is visualised as a combination of fluidized bed and packed bed in series, observations made for the total pressure drop do not tally with the summation of pressure drops of the packed and fluidized beds taken separately. Rigorous analysis of this aspect is yet to be made.

The utility of the information published so far for the design of semifluidizers of larger diameters will still pose a problem for scaling up. Information published on heat and mass transfer is very meagre and there is wide scope for researches to be carried out.

The programme envisaged by this department includes all the above aspects and work is in progress.

C H A P T E R - II

LITERATURE SURVEY

LITERATURE SURVEY

Semi-fluidization is a new type of fluid-solid contacting technique which has been reported in the last decade only. Like the packed and the fluidized bed techniques, this is also a two-phase phenomena. A semifluidized bed is a compromise between the packed and the fluidized bed conditions and can be achieved in a conventional fluidizer by incorporating certain modifications in the column construction.

In case of batch fluidization, if the free expansion of the bed is restricted by the introduction of a porous disc or sieve, some of the particles will be carried upwards and will form a packed bed at the top. At the bottom the remaining material will be in a fluidized state. Such a fluidized bed having restricted expansion, comprises the features of both fixed and fluidized beds and is termed as "Semifluidized bed".

Fluidized bed technique as compared to fixed bed has specific advantages. These are :-

(i) the fluidized bed ensures uniform contact of the fluid with all the particle surfaces.

(ii) it prevents segregation of solids because of the turbulence

(iii) the temperature variation is minimized i.e., local hot spots are avoided

(iv) has a lesser pressure drop than the fixed bed.

As against these the fluidized bed suffers from certain serious defects like :-

(i) Loss of driving potential for transfer processes within the bed because of the intense back-mixing.

(ii) Attrition and elutriation of solid particles which necessitate costly dust recovery system.

(iii) Non-availability of necessary free space above the bed, and

(iv) Erosion of the containing vessel.

As a result, a wholesome substitution of fixed bed method by fluidized ones has not been recommended. An answer to this problem can be the use a semifluidized bed. By chosing suitable parameters like restraint position, fluid velocity etc., it is possible to have packed and fluidization conditions in the same set-up. Further semi-fluidization offers greater flexibility of operation.

Since semifluidized beds comprise the features of both packed and fluidized beds these may be employed to serve as a unique combination of back- mix and tubular- flow reactors in series, whose relative lengths can be varied simply by adjusting the overall concentration of solids, to yield the most optimum driving potentials for momentum, heat and mass transfer without disturbing other operating variables. Semi-fluidization technique will thus have immense applications in various fields of Chemical Engineering in the near future.

Its application in the field of reaction kinetics has already been initiated. Babu Rao et-al.[1] proposed a new type of combined mixed and tubular reactor system (MT reactor) based on the principle of semi-fluidization, which is useful, especially for fast exothermic reactions like the vapor phase oxidation and chlorination of hydrocarbons. In exothermic reactions, an optimum performance may be obtained with an MT reactor and depending on the prevailing conditions, a higher conversion would be obtained or a small residence time. Moreover, a semifluidized bed reactor can be operated with steep temperature gradients in one section and an uniform temperature in the other, with practically no elutriation of solids and low pressure drop.

Use of this technique in mass transfer studies have shown that the magnitudes of mass transfer coefficients can be controlled approximately linearly, and can be maintained within the limits of a completely fixed bed and fully fluidized bed by bed expansion alone. In case of heat transfer, it is possible to adjust the value of heat transfer coefficient in a semifluidized bed by adjusting the position of the top sieve plate or by adjusting the total amount of the solid particles or both.

A review of the literature on semi-fluidization was made by Roy and Sarma[2] sometime back. In general, studies relating to various aspects of semi-fluidization can be broadly classified as :

(i) Hydrodynamic studies.

(ii) Studies relating to mass transfer, heat transfer and reaction kinetics.

HYDRODYNAMIC STUDIES:

Studies relating to the hydrodynamics of semi-fluidization are relatively more and various aspects of the semi-fluidization phenomena have been reported. The studies related to hydrodynamics can further be subdivided into -

(i) Studies oriented towards the prediction of the minimum and the maximum semi-fluidization velocities,

(ii) Studies oriented towards the prediction of packed bed formation,

(iii) Studies relating to the prediction of total pressure drop in a semifluidized bed, and

(iv) Miscellaneous hydrodynamic studies.

I. Minimum and maximum semi-fluidization velocities:

Minimum semi-fluidization velocity :-

Fan and coworkers [3,4,5] were the pioneer investigators in the field of semi-fluidization. They had initiated their work with studies on mass transfer[3]. Later on they studied the characteristics of semifluidized beds of single size particles both in liquid-solid[4] and gas-solid systems[5]. Although no correlation was suggested for the direct prediction of the minimum semi-fluidization velocity, they commented that this velocity is dependant on the fluid and the particle characteristics, and also on the relative quantity of solid particles to the column height (h_s/h, also called the reciprocal of the bed expansion ratio in semi-fluidization). When h_s/h approaches almost unity, the minimum semi-fluidization velocity approaches the value of minimum fluidization velocity (G_{mf}), and when h_s/h approaches almost equal to zero i.e., the top restraint is kept at a much higher level as compared to the initial static bed, the value approaches the terminal velocity or the maximum semi-fluidization velocity. Thus the minimum semi-fluidization velocity has a value between the onset of fluidization and the maximum semi-fluidization velocity depending on the value of h_s/h , which has the limiting value of zero and unity. Both Fan et.al.(Loc. cit.) and Babu Rao et.al.(loc. cit.) reported that this velocity can be obtained directly from the plot between total pressure drop and fluid mass velocity. Fan et. al. observed similar behaviour in the liquid-solid and gas-solid systems of semi-fluidization. However they remarked that the understanding of the gas-solid systems is still far from complete owing to the complexity of the aggregative bed pattern and had recommended further investigations before confirming the similarity in behaviour between the two types of systems.

Based on their experimental studies in liquid-solid systems, Poddar and Dutt[6] proposed the following equation for the prediction of minimum semi-fluidization velocity :

$$18\, Re_{osf} + 2.7\, Re_{osf}^{1.687} = 0.966\, \varphi_s^{0.88}\, Ga \cdot \left[1 - \frac{h_s}{h}(1-\epsilon_{pa})\right]^{4.7} \quad \ldots \quad (2.1)$$

where,

$$Re_{osf} = \frac{d_p\, G_{osf}}{\mu} \quad \ldots \quad (2.1a)$$

In this method, the value of G_{osf} has to be calculated by a trial and error procedure.

Kurian and Raja Rao[7] have suggested the following two methods to estimate theoretically the minimum semi-fluidization velocity. The first method is based on the expansion behaviour of the fluidized bed and almost idential to that given by Poddar and Dutt. They gave a graphical correlation between $\epsilon_f^{4.7} \cdot Ga \cdot \varphi_s^3$ and Re_p', where

$$Re_p' = \frac{d_p\, \varphi_s\, G}{\mu} \quad \ldots \quad (2.2a)$$

Also,

$$\epsilon_f^{4.7} \cdot Ga \cdot \varphi_s^3 = \left[1 - \frac{(1-\epsilon_{pa})}{R}\right]^{4.7} Ga\, \varphi_s^3 \quad (2.2b)$$

The second method for predicting this value is based on the correlation for the height of a packed section and the corresponding semi-fluidization velocity in a semifludized bed. From the experimental semi-fluidization data, they gave the following equation for the packed bed prediction -

$$\frac{G_{sf} - G_{mf}}{G_t - G_{mf}} = 0.61 \left(\frac{h - h_{pa}}{h - h_s}\right)^{-1.2} \quad \ldots \quad (2.3)$$

At the onset of semi-fluidization, the packed section is not formed ($h_{pa} = 0$) and hence equation (2.3) reduces to

$$\frac{G_{osf} - G_{mf}}{G_t - G_{mf}} = 0.61 \quad \left(\frac{R}{R-1}\right)^{-1.2} \quad \ldots \qquad (2.4)$$

They have compared the values of G_{osf} for the experimental conditions with those obtained by equations (2.2) and (2.3). The comparatively large deviations of the values predicted by the second method was attributed to the considerable error involved in the measurement of the somewhat smaller heights of packed section (h_{pa}) particularly in the initial stage of packed bed formation.

An alternative approach has been made by Roy and Sarma[8] for the prediction of minimum semifluidization velocity from a knowledge of the fluidization characteristics of the system. They developed correlation relating the onset of semi-fluidization with the minimum fluidization velocity in terms of various system parameters for liquid-solid semi-fluidization. The final correlations given are :

For non-spherical particles,

$$\frac{G_{osf}}{G_{mf}} = 1.625 \left(\frac{D_c}{d_p}\right)^{0.266} \left(\frac{\rho_s}{\rho_f}\right)^{-0.228} (R)^{0.585} \qquad (2.5a)$$

For spherical particles,

$$\frac{G_{osf}}{G_{mf}} = 1.875 \left(\frac{D_c}{d_p}\right)^{0.266} \left(\frac{\rho_s}{\rho_f}\right)^{-0.228} (R)^{0.585} \qquad (2.5b)$$

The onset of fluidization velocity was calculated from Leva's simplified equation. By a similar approach, Roy and Sen Gupta[9] have suggested equations for the prediction of minimum semi-fluidization velocity from minimum fluidization velocity in gas-solid systems. The equations are:

For non-spherical particles,

$$\frac{G_{osf}}{G_{mf}} = 2.66 \times 10^{2} \left(\frac{D_c}{d_p}\right)^{0.62} \left(\frac{\rho_s}{\rho_f}\right)^{-1.00} (R)^{0.50} \qquad \ldots(2.6a)$$

For spherical particles,

$$\frac{G_{osf}}{G_{mf}} = 3.4 \times 10^{3} \left(\frac{D_c}{d_p}\right)^{1.11} \left(\frac{\rho_s}{\rho_f}\right)^{-1.78} (R)^{0.89} \qquad \ldots(2.6b)$$

Maximum semi-fluidization velocity:-

It is the fluid velocity corresponding to which the entire solid particles are transferred to the upper section of the column to give rise to a packed bed below the top restraint almost equal to the initial static bed. This velocity also corresponds to the terminal free fall velocity of the particles. Three different methods have been suggested by Fan et.al.(loc.cit.) for the prediction of the maximum semi-fluidization velocity.

Method-A: By linear extrapolation of expanded bed voidage (ϵ_f) vs. fluid mass velocity curve to the value of ϵ_f=1.0.

Method-B: By extrapolation of h_{pa}/h_s vs. fluid mass velocity curve to the value of h_{pa}/h_s = 1.0.

Method-C: By calculation of free fall terminal velocity.

The first method is based on the fact that above the maximum semi-fluidization velocity, if the bed expansion is not restricted, all the particles would have been carried out of the column and consequently the porosity of the bed would approach unity. Method-B is based on the fact that all the particles are shifted to the packed section from the fluidised section at the maximum semi-fluidization point. Therefore the height of the packed section at this point becomes equal to that of the static bed height, provided the voidage of the packed section in both the cases (fixed bed condition and fixed bed of the semi-fluidization condition) is assumed to be unchanged. The third method is based on the proposition that at the maximum semi-fluidization point the settling velocity of individual particles becomes equal to the upward flowing fluid velocity. The terminal settling velocity for a single particle falling in an infinite fluid medium can be calculated by Stokes' law, the intermediate law or Newton's law, depending on the range of the particle Reynolds number. Values obtained by the three different methods were compared (Table 2.A).

T A B L E- 2.A

Comparison of maximum semi-fluidization velocity as obtained by Fan et.al.(loc.cit.)

Experimental series (particles)	Maximum semi-fluidization velocity, lbs./hr.ft^2		
	Method-A	Method-B	Method-C
A (50-60 mesh)	23000	28000	21100
C (40-45 mesh)	36600	40000	33500

As can be seen from the above table, the values calculated by method (B) were always greater than the values determined by method (A), probably owing to the following reasons-

(i) However close cut particles used may be, there is definite size distribution for every sample. The maximum semi fluidization velocity for the largest particles of the sample will be greater than that for the average size particles. As a result, the value calculated by this method will be greater than the values obtained for completely uniform particles of the average size.

(ii) The assumption of the fact that, the initial static bed porosity is equal to the packed bed porosity of a semi-fluidized bed is not correct. Moreover, the complete formation of packed bed at the top is not always achieved experimentally. Hence the value obtained by extrapolation of h_{pa}/h_s equal to unity, is higher.

(iii) It is well known that the fluid along the axis of the column moves faster than the fluid adjacent to the wall and hence the particles near the wall may be falling downwards while the particles along the center line of the column are already held in suspension.

The difference of the maximum semi-fluidization velocities estimated by method (C) from the values determined by either of the previous methods cannot be explained merely as due to the experimental error. The equation for gravity settling is derived for a single particle. There must be a definite influence of the existence of other particles as well as the effect of column wall and supports.

Poddar and Dutt (loc.cit.) have proposed the following equation for the prediction of the maximum semi-fluidization velocity in liquid-solid systems -

$$18\, Re_{msf} + 2.7\, Re_{msf}^{1.687} = Ga \qquad \ldots \qquad (2.7)$$

where,

$$Re_{msf} = \frac{d_p\, G_{msf}}{\mu} \qquad \ldots \qquad (2.7a)$$

Poddar and Dutt[10] also tried to correlate the maximum semi-fluidization velocities as calculated above with the minimum fluidization velocity obtained from a generalised equation proposed by Wen and Yu[11],

$$Re_{mf} = \left[(33.7)^2 + 0.0408\, Ga\right]^{\frac{1}{2}} - 33.7 \qquad \ldots \qquad (2.8)$$

From equations (2.7) and (2.8), the final relation between the minimum fluidization and the maximum semi-fluidization velocities as derived by them is,

$$\frac{18 \cdot Re_{msf} + 2.7\, Re_{msf}^{1.687}}{Re_{mf}} = \alpha + \sqrt{\alpha^2 + \beta\, Ga} \qquad \ldots \qquad (2.9)$$

where, $\alpha = 826$ and $\beta = 24.51$.

Kurian and Raja Rao (loc.cit.) used the methods of Fan et.al.(loc.cit.) for the estimation of the maximum semi-fluidization velocity. Comparatively lower values were obtained by them, when method-(A) was followed. The authors remarked that, due to some stratification observed at very high voidages ($\epsilon_f > 0.8$), the measured voidage values could be slightly higher, and hence extrapolation of the voidage curve to $\epsilon_f = 1.0$ might have led to a somewhat lower value of G_{msf} than what could be obtained on the basis of uniform bed density. This method of obtaining maximum semi-fluidization velocity from voidage data would involve considerable error. Similar observations were made by Babu Rao and Doraiswamy[12], while reporting the results of semi-fluidization studies on gas-solid systems.

Roy and Sarma[13] developed the correlation relating the maximum semi-fluidization with the minimum fluidization velocity in terms of various system parameters for liquid-solid systems as,

$$\frac{G_{msf}}{G_{mf}} = 5.71 \left(\frac{D_c}{d_p}\right)^{0.42} \left(\frac{\rho_s}{\rho_f}\right)^{-0.67} \qquad \ldots \qquad (2.10)$$

II. <u>Prediction of packed bed height in semi-fluidization</u>:

The knowledge of packed bed formation under semifluidized condition is very important, as this determines the relative distribution of particles in the packed and the fluidized beds.

Pioneer investigations were reported by Fan et.al (loc. cit.). Using the material balance between the completely fluidized and the packed bed and assuming that the particles are uniformly distributed in a fluidized bed, the movement of a particle in the suspension is completely independent of other particles, and the suppression of the expansion of the sespensions and subsequent formation of the packed section does not change the average particle distance in the fluidized section; and the voidage of the packed section is constant and is that of the least dense static bed under resting conditions, the following equation for the height of the packed section was obtained by them,

$$h_{pa} = (h_f - h)\ \frac{1 - \epsilon_f}{\epsilon_f - \epsilon_{pa}} \qquad \ldots \qquad (2.11)$$

The observed and calculated values of the packed bed formation tallied well upto a value of $\epsilon_f = 0.8$.

In addition to above, they suggested an all-together different method for the prediction of packed bed in liquid-solid and gas-solid systems. Resorting to dimensional analysis and use of momentum and continuity equations for particulate fluidization, the following expression was derived.

$$f\ \left(\frac{h - h_s}{h - h_{pa}}\right),\ \left(\frac{G_{sf} - G_{mf}}{G_t - G_{mf}}\right) = 0 \qquad \ldots \qquad (2.12)$$

i.e., when $(h-h_s)/(h-h_{pa})$ is plotted against $(G_{sf}-G_{mf})/(G_t-G_{mf})$ on log-log coordinates, a straight line is obtained. In this G_t values are either calculated or obtained from extrapolation and G_{mf} is to be calculated using the following equation[14],

$$G_{mf} = 688\ \frac{d_p^{1.82}\left[\rho_f\ (\rho_s - \rho_f)\right]^{0.94}}{\mu^{0.88}} \qquad \ldots \qquad (2.13)$$

The authors found good agreement between the experimental data and the theoretical values.

The equation proposed by Poddar and Dutt[15] for the formation of packed bed is -

$$h_{pa} = \frac{h_s (1 - \epsilon_{pa})}{\epsilon_f - \epsilon_{pa}} - \frac{h (1 - \epsilon_f)}{\epsilon_f - \epsilon_{pa}} \quad \ldots \quad (2.14)$$

where, ϵ_f can be related as

$$\epsilon_f = \left[\frac{18 \, Re_p + 2.7 \, Re_p^{1.687}}{Ga} \right]^{0.2125} \quad \ldots \quad (2.15)$$

Roy and Sarma[16] have introduced the minimum semi-fluidization velocity term in place of the minimum fluidization velocity in equation (2.12) of Fan et.al. and developed an expression which may be written as -

$$\frac{h - h_s}{h - h_{pa}} = \left(\frac{G_{sf} - G_{osf}}{G_{msf} - G_{osf}} \right)^{0.2} \quad \ldots \quad (2.16)$$

III. <u>Prediction of total pressure drop in semifluidized bed</u>:

Measurements of total pressure drop occurring in semi-fluidization have been first reported by Fan et.al.(loc.cit.) for gas-solid systems and the measured values have been compared with those calculated from theoretical equation. In case of semi-fluidization, the total pressure drop should be ideally the algebraic sum of the pressure drop across the fluidized section and the packed section, as both are aligned in series in the direction of flow. Hence,

$$\Delta P_T = \left(\frac{\Delta P}{L}\right)_f (h - h_{pa}) + \left(\frac{\Delta P}{L}\right)_{pa} h_{pa} \quad \ldots \quad (2.17)$$

For fluidized section,

$$\left(\frac{\Delta P}{L}\right)_f = (1 - \epsilon_f)(\rho_s - \rho_f) \quad \ldots \quad (2.18)$$

For packed section, using Ergun's equation,

$$\left(\frac{\Delta P}{L}\right)_{pa} = \frac{1}{g_c}\left[150\,\frac{(1-\epsilon_{pa})^2}{\epsilon_{pa}^3}\,\frac{\mu u}{d_p^2} + 1.75\,\frac{(1-\epsilon_{pa})}{\epsilon_{pa}^3}\,\frac{Gu}{d_p}\right] \quad \ldots \quad (2.19)$$

Therefore, the total pressure drop is,

$$\Delta P_T = \left(\frac{\Delta P}{L}\right)_{pa} h_{pa} + \left(\frac{\Delta P}{L}\right)_f (h - h_{pa})$$

$$= \frac{1}{g_c}\left[150\,\frac{(1-\epsilon_{pa})^2}{\epsilon_{pa}^3}\,\frac{\mu u}{d_p^2} + 1.75\,\frac{(1-\epsilon_{pa})}{\epsilon_{pa}^3}\cdot\frac{Gu}{d_p}\right]\left[(h_f - h)\,\frac{(1-\epsilon_f)}{\epsilon_f - \epsilon_{pa}}\right]$$

$$+ \left[h_f - \frac{(1-\epsilon_{pa})(h_f - h)}{\epsilon_f - \epsilon_{pa}}\right](1-\epsilon_f)(\rho_s - \rho_f) \quad \ldots (2.20)$$

Fan et.al. measured the pressure drop in fixed and fluidized beds separately and the total pressure drop was obtained using equation (2.17). This has been compared with the observed bed pressure drop and also with that calculated using equation (2.20).

It has been observed that the experimental values are nearer to those calculated by using equation (2.17), whereas, equation (2.20) gave lower values. The authors explained the deviations as due to the difficulty in using equation (2.20), which involves the determination of packed and fluidized bed porosities accurately. Further, the assumption that the porosity in the packed section is equal to that of the least dense static bed is not very accurate, because the top bed is under compression due to the upward movement of the fluid. This results in the variation of packed bed porosity and Ergun's equation is too sensitive to this variation.

Kurian and Raja Rao (loc.cit) calculated the overall pressure drop in a liquid-solid semifluidized bed with the help of equation (2.20) and found it to be valid strictly for spherical particles (glass beads) of larger diameter. In case of other comparatively smaller and irregular shaped particles, the observed pressure drop was found to be greater than that given by equation (2.20), owing to the partial blockage of the screen holes of the restraining plate by the particles. The additional pressure drop (ΔP_a), observed with all the smaller and non-spherical particles was found to be a function of three factors viz., G, d_p and h_{pa}. The authors obtained the following empirical correlation for the additional pressure drop in the screen,

$$\Delta P_a = 2.10 \times 10^{-3} \, G_{sf}^{1.56} \, d_p^{-0.94} \, h_{pa}^{0.59} \qquad \ldots \quad (2.21)$$

when 2.10×10^{-3} is dimensional constant. The correlation for overall pressure drop in a semifluidized bed was obtained by adding equation (2.21) for ΔP_a to equation (2.20) and the resulting equation is -

$$\Delta P_T = \frac{1}{g_c}\left[150\ \frac{(1-\epsilon_{pa})^2}{\epsilon_{pa}^3}\cdot\frac{\mu u}{d_p^2} + 1.75\ \frac{(1-\epsilon_{pa})}{\epsilon_{pa}^3}\cdot\frac{G u}{d_p}\right]$$

$$\left[(h_f - h)\ \frac{(1-\epsilon_f)}{\epsilon_f - \epsilon_{pa}}\right] + \left[h_f - \frac{(1-\epsilon_{pa})\ (h_f - h)}{\epsilon_f - \epsilon_{pa}}\right]$$

$$(1-\epsilon_f)\ (\rho_s - \rho_f)\ + 2.10\times10^{-3}\ G_{sf}^{1.56}\ d_p^{-0.94}\ h_{pa}^{0.59} \qquad \ldots \qquad (2.22)$$

A comparison of the experimental values of the overall pressure drop in a semifluidized bed with those estimated from equation (2.22) showed on average deviation of 12% and a maximum deviation of 20%.

In order to overcome the wide discrepancies between the experimental and calculated values of semifluidized bed pressure drops, a correction factor was suggested by Roy and Sengupta[17] in terms of system parameters for gas-solid semifluidization. The correction factor is given as follows:

For non-spherical particles,

$$C = \frac{(\Delta P_T)_{actual}}{(\Delta P_T)_{calculated}}$$

$$= 1.95 \times 10^{-1}\left[\left(\frac{D_c}{d_p}\right)^{-0.24} \left(\frac{\rho_s}{\rho_f}\right)^{0.55} \left(\frac{h_s}{D_c}\right)^{-0.94} (R)^{0.72}\right.$$

$$\left.\left(\frac{h_{pa}}{h_s}\right)^{0.29}\right] \qquad \ldots \qquad \ldots \qquad (2.23a)$$

For spherical particles,

$$C = \frac{(\Delta P_T)_{actual}}{(\Delta P_T)_{calculated}}$$

$$= 7.3 \times 10^{-3} \left[\left(\frac{D_c}{d_p}\right)^{-0.53} \left(\frac{\rho_s}{\rho_f}\right)^{1.18} \left(\frac{h_s}{D_c}\right)^{-2.05} (R)^{1.56} \left(\frac{h_{pa}}{h_s}\right)^{0.64} \right] \quad \ldots \quad \ldots \quad (2.23b)$$

The calculated values were obtained with the help of equation (2.20).

IV. Miscellaneous hydrodynamic studies:

On the basis of their hydrodynamic studies in liquid-solid semi-fluidization, Sunkoori et.al.[18] suggested an indirect relationship for packed bed formation. The ratio of the free surfaces during free and restricted fluidizations, was related with the fluid mass velocity and the particle size as -

$$\left(\frac{h_s}{h'}\right) d_p^2 = A. e^{0.1G} \quad \ldots \quad \ldots \quad (2.24)$$

where, A is a function of (h/h_s) which can be expressed in the form,

$$A = 0.007 (h/h_s)^{2.5} \quad \ldots \quad \ldots \quad (2.25)$$

A phase diagram showing the regions of restricted packed bed, fluidized bed and semifluidized bed was also presented by them by plotting the variation of bed height with fluid mass velocity. In addition, a plot of modified friction factor (f_m) against particle Reynolds number (Re_p) was suggested and the data were found to fit well for all the above cases.

STUDIES ON HEAT TRANSFER, MASS TRANSFER & REACTION KINETICS:

I. Heat Transfer:-

The first heat transfer study was reported by Rao and Kaparthi[19]. They have investigated wall-to-fluid heat transfer in semifluidized beds using air as the medium. Heat transfer coefficient was related as follows:

$$Nu_p = 0.72\ (Re_p)^{1.1}\ \left(\frac{1 - \epsilon}{\epsilon}\right)^{0.4} \quad \ldots \quad (2.26)$$

where, ϵ is the porosity of the overall bed.

The investigations undertaken by Varma and coworkers[20] relate to the study of heat transfer characteristics of semifluidized beds using liquid-solid systems. They observed that the values of the heat transfer coefficients in semifluidized beds increase with increase in the overall concentration of solids in the system and lie within the limits of packed and fluidized beds. Similar results were reported by Rao and Kaparthi, who used air as the fluidizing medium. The increase in the values of heat transfer coefficients with increase in particle concentration may be the result of greater turbulence created within the bed. The dimensionless empirical correlations developed are -

$$Nu_p = 0.00285 (Re_p)^{1.21}\ (Pr.)^{0.33}\ (R)^{-1.1}\ \left(\frac{d_p}{D_t}\right)^{-0.58} \quad \ldots \quad \ldots \quad (2.27)$$

for glass systems and

$$Nu_p = 0.0032\ Re_p^{1.21}\ Pr^{0.33}\ (R)^{-1.1}\ \left(\frac{d_p}{D_t}\right)^{-0.58} \qquad (2.28)$$

for alumina systems.

II. Mass Transfer:-

Investigations in the field of semi-fluidization were started by Wen et.al. with mass transfer studies. Experiments were conducted with benzoic acid- water system in semi-fluidized beds. The mass transfer data were correlated in terms of the J_d - factor and the modified Reynolds number. The mass transfer coefficients were calculated on the basis of the over-all logarithmic mean driving force for both packed and fluidized bed mass transfer. The expression[21] for benzoic acid- water system was

$$J_d = 1.865\ (Re_m)^{-0.48} \quad \ldots \quad \ldots \quad (2.29)$$

for $5 < Re_m < 30$.

Tripathi and coworkers[22] have presented the results of their studies on particle- fluid mass transfer in semifluidized beds using benzoic acid- , cinnamic acid- and 2- naphthol- water systems. The data have been correlated in terms J_d- factor and particle Reynolds number.

For benzoic acid,

$$J_d = 2.743\ (Re_p)^{-0.484} \quad \ldots \quad \ldots \quad (2.30)$$

For Cinnamic acid,

$$J_d = 2.35\ (Re_p)^{-0.484} \quad \ldots \quad \ldots \quad (2.31)$$

For 2- napthol,

$$J_d = 1.865\ (Re_p)^{-0.484} \qquad \ldots \qquad \ldots \qquad (2.32)$$

The variation in the mass transfer rates for different systems was attributed to the diffusivity of the solutes and the degree of compression of the particles in the semi-fluidized state.

Further study in the mass transfer coefficient was made by Govindarajan[23] for benzoic acid- water system. The expression for volumetric mass transfer coefficient was given as follows:

$$K_{L_a} = 2.512 \times 10^{-5}\ (Re_p)^{2.51}\ (R)^{-1.03} \qquad \ldots \qquad (2.33)$$

III. <u>Reaction Kinetics</u>:-

Cholette and Blanchet[24] have shown that a combination of mixed and tubular reactors (MT reactors) is very often more efficient than either of these reactors operated independently. This is especially so, in exothermal reaction where an optimum performance may be obtained with MT reactors. The theoretical advantage of the MT combination can be practically realised in a simple reactor system utilising the principle of semi-fluidization. Keeping this in view Babu Rao and Doraswamy (loc.cit.) initiated their work on the development of a semifluidized MT reactor. Incidently they conducted experiments on gas-solid semi-fluidization. The authors introduced a new dimensionless group called the semi-fluidization group (sf), which along with Archimedes number (Ar.) have been correlated against the ratio of semi-fluidization velocity to terminal velocity as :-

$$\frac{G_{sf}}{G_t} = K\ (Ar.)^{-0.150}\ (Sf.)^{-0.186} \qquad \ldots \qquad (2.34)$$

Where, $K = \frac{17.3}{D^{0.372}}$ (D, diameter of reactor in ft.) (2.34a)

Though considerable work has already been reported in the field of semi-fluidization for the prediction of onset and maximum semi-fluidization velocities and the packed bed formation, it can be seen that all the system parameters have not been studied exhaustively by any of the earlier authors. Certain aspects like mixed particle systems, effect of length to diameter ratio of semifluidizer, effect of nature and shape of particles etc. are yet to be explored. Studies on pressure drop in semi-fluidization require a more rigorous analysis of the entire phenomena and this aspect has large scope for investigation. Since gas-solid systems are more likely to be adopted for industrial practice and because of the aggregative nature of these systems, a detailed study of this is very important. In the field of mass and heat transfer also only limited work has been reported. There is scope for studies in these areas. So far experimental studies on semi-fluidization are all confined to column size not more than 2 to 3 inches inside diameter. These present lot of problems in scaling up and hence it is recommended that pilot plant studies in semifluidizers of considerably larger diameter be carried out. The beginning in reaction kinetics has not yet been made and this requires immediate attention.

NOMENCLATURE

Ar = Archimedes number, dimensionless group,

$$\frac{d_p^3 \ \rho_s \ (\rho_s - \rho_f) \ g}{\mu^2}$$

C = Correction factor for pressure drop correlation in semi-fluidization.

D = Diameter of the reactor, L

D_c, D_t = Diameter of the column (semifluidizer), L

d_p = Particle diameter, L

f = Function.

g_c = Gravitational constant, L θ^{-2}

Ga = Galileo number, dimensionless group,

$$\frac{d_p^3 \ \rho_f \ (\rho_s - \rho_f) \ g}{\mu^2}$$

G = Mass velocity of fluid, $ML^{-2}\theta^{-1}$

G_{mf} = Minimum fluidization mass velocity, $ML^{-2}\theta^{-1}$

G_{msf} = Maximum semi-fluidization mass velocity, $ML^{-2}\theta^{-1}$

G_{osf} = Minimum (onset) semi-fluidization mass velocity, $ML^{-2}\theta^{-1}$

G_{sf} = Semi-fluidization mass velocity, $ML^{-2}\theta^{-1}$

G_t = Free fall terminal mass velocity of particle (also called maximum semi-fluidization mass velocity), $ML^{-2}\theta^{-1}$

h = Overall height of column (or semifluidized bed), L

h_s = Height of initial static bed, L

h_{pa} = Height of packed section in semi-fluidization, L

h_f = Height of fully fluidized bed, L

h' = Height of fluidized bed in restricted fluidization, L

K = Constant of equation

K_{L_a} = Volumetric mass transfer coefficient, $M\theta^{-1}L^{-3}(\Delta C)^{-1}$

MT = Mixed and tubular reactor

Nu_p = Nusselt number based on particle diameter, dimensionless group, hd_p/K_f

ΔP_a = Additional pressure drop in the restraining plate, FL^{-2}

$(\frac{\Delta P}{L})_f$ = Pressure gradient across fluidized bed, FL^{-3}

$(\frac{\Delta P}{L})_{pa}$ = Pressure gradient across packed bed, FL^{-3}

ΔP_T = Overall pressure drop across the semifluidized bed, FL^{-2}

Pr = Prandtl number, dimensionless group, $C_p \mu_f/K_f$

R = Bed expansion ratio in semi-fluidization, dimensionless, h/h_s

Re_m = Modified Reynolds number, dimensionless,

$$\frac{d_p \; G}{\mu_f(1-\epsilon_{pa})}$$

Re_p = Reynolds number based on particle diameter, dimensionless, $d_p \; G/\mu_f$

Re_{mf} = Particle Reynolds number corresponding to minimum fluidization condition, dimensionless, $\frac{d_p \; G_{mf}}{\mu_f}$

Re_{msf} = Particle Reynolds number corresponding to maximum semi-fluidization condition, dimensionless,

$$\frac{d_p\ G_{msf}}{\mu_f}$$

Re_{osf} = Particle Reynolds number corresponding to minimum (onset) semi-fluidization condition , dimensionless,

$$\frac{d_p\ G_{osf}}{\mu_f}$$

Sf = Semi-fluidization group, $(W_S - W_P)/(h - h_s)^3\ \rho_s$

u = Linear velocity of fluid, $L\ \theta^{-1}$

W_P = Total weight of solid in the packed bed section in semi-fluidization, M

W_S = Initial weight of solid in static bed, M

Greek letters :-

Δ = Finite change of variable

α = Constant

β =Constant

ψ = Function

Φ = Function

Φ_s = Sphericity of particle

$\mu(\mu_f)$ = Viscosity of fluid, $ML^{-1}\ \theta^{-1}$

ρ_f = Density of fluid, ML^{-3}

ρ_s = Density of solid, ML^{-3}

ϵ_f = Porosity of fluidized bed or fluidized section of semifluidized bed, dimensionless

ϵ_{pa} = Porosity of packed bed or packed section of semi-fluidized bed, dimensionless

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C H A P T E R - III

EXPERIMENTAL ASPECTS (LIQUID-SOLID SYSTEM)

EXPERIMENTAL ASPECTS(LIQUID-SOLID SYSTEM)

EXPERIMENTAL SET-UP :

The experimental set-up consists primarily of the following components as shown in fig.- 3.1 and plates- 1.A and 1.B.

1. Semifluidizer(3):- It is a perspex column of 2.5 cms. inside diameter and 100 cms. long inserted between two flanges and provided with an inclined feeder (7) at a height of about 21.0 cms. from the base for intermediate addition and removal of materials without dismantling the whole assembly. Two pressure taps are provided in the flanges, one at the top and the other at the bottom, just below the grid. The grid is made up of a 100 mesh stainless steel screen. A few intermediate pressure taps are also provided on both sides of the column at regular intervals. Plate-2 shows the details of the semifluidizer.

2. Movable restraint (4) :- It is specially designed such that it has smooth movement along the inner wall of the column. At the same time, the restraint remains in tact, so that there is no water leakage in between its sides and the inner wall of the semifluidizer. The movable restraint is made up of 100 mesh stainless steel screen placed between two perspex rings, the out side diameter of which is very nearly the same as the inside diameter of the column. A brass rod

of 3 mm. diameter is connected to it as shown in figure. This rod moves through a hole in rubber cork fitted to top of the column and helps the movement of the restraint to any position within it.

3. Conical distributor and calming section (8).

4. Rotameters :- One for higher range of flow and the other for the lower range.

5. Water reservoir (13).

6. Recirculating pump (12).

7. Manometer panel board.

8. Thermometer pocket

Water from the reservoir was pumped through the semifluidizer. Calibrated rotameters (one for the lower range and the other for the higher range) were used to measure the water flow rate. The calibration charts are given in figs.- 3.2 and 3.3 and the tables in the appendix- A. Two manometers with carbon tetra-chloride (dyed) and mercury as the manometric liquids were used to determine the pressure drop across the semifluidized bed. Two more similar sets of manometers were provided for the measurement of pressure drops across the intermediate tappings. The inlet temperature of water was noted by a thermometer (10).

EXPERIMENTAL PROCEDURE :

The various experimental procedures followed in these studies are described below in detail .

I) <u>Determination of fixed bed porosity</u> :-

A weighed amount of material was charged to the column and the bed was fluidized. It was then allowed to settle slowly and the bed height was noted. This was repeated several times till the height was reproducible. This was taken as the initial fixed bed height. The flow of water was then turned off. The water in the column was allowed to drain through a separate capillary tube at the bottom and the volume of water entrapped in the voids was collected very carefully and measured accurately. This was repeated several times till the volume of water collected was almost constant. From the void volume, fixed bed porosity was calculated. The experiments were repeated for each of the samples used in semi-fluidization studies.

II) <u>Hydrodynamic studies of the semi-fluidization phenomena</u> :-

To begin with, a blank run was conducted with the bottom grid and the top restraint in position. Within the range of flow rates studied, the pressure drop was found to be negligible.

A sample of material was charged to the column and the fixed bed height was recorded as described earlier. By addition or removal of material through the inclined tube, the fixed bed height was adjusted for a desired value. The position of the movable top restraint was then adjusted for a fixed bed expansion ratio. The water flow rate was increased slowly and kept steady for sometime for each reading. Pressure drop across the bed was carefully recorded along with the flow-rate for the fixed and fluidized bed conditions. With further increase of flow, a portion of the particles in the fluidized bed started moving up and formed a packed bed below the restraint (Plate-3). The formation of packed bed was accompanied by a sudden rise in the pressure drop. In subsequent observations the packed bed formations were noted accurately along with the pressure drop and flow rate.

After the run was complete, the top restraint was moved to a new position and the entire procedure was repeated.

In order to increase the initial fixed bed hight to another definite value, additional amount of materials were added through the inclined feeder and the above procedure was repeated.

After completion of a set of runs the material was taken out through the inclined tube and the column was thoroughly washed. A fresh sample of material was then added and the above process was repeated.

Provision was made for the measurement of pressure drops at various stages of packed bed formation, but these were not used in the present set of experiments due to difficulties in forming packed bed exact to the point of the pressure tappings.

III) Bed Expansion studies :-

Bed expansion data provides an alternative method for prediction of minimum and the maximum semi-fluidization velocities and hence the studies were made.

A weighed amount of a particular material was charged to the column and the initial fixed bed height was recorded in a similar way as described previously. The flow of water was then slowly increased and the fluidized bed heights were recorded along with the flow rates. At higher flow rates, some fluctuations were observed at the top of the bed. At these flow rates, the bed was allowed to operate for sometime and highest and the lowest readings were recorded and their average value was taken as the expanded bed height. From the knowledge of fixed bed porosity (determined as described earlier), fixed bed height and the expanded bed heights, the expanded bed voidages are calculated.

Physical properties of the fluids used in experiments are given in table-3.1 and that of solids along with ranges of variables studied are given in table -3.2.

TABLE- 3.1.

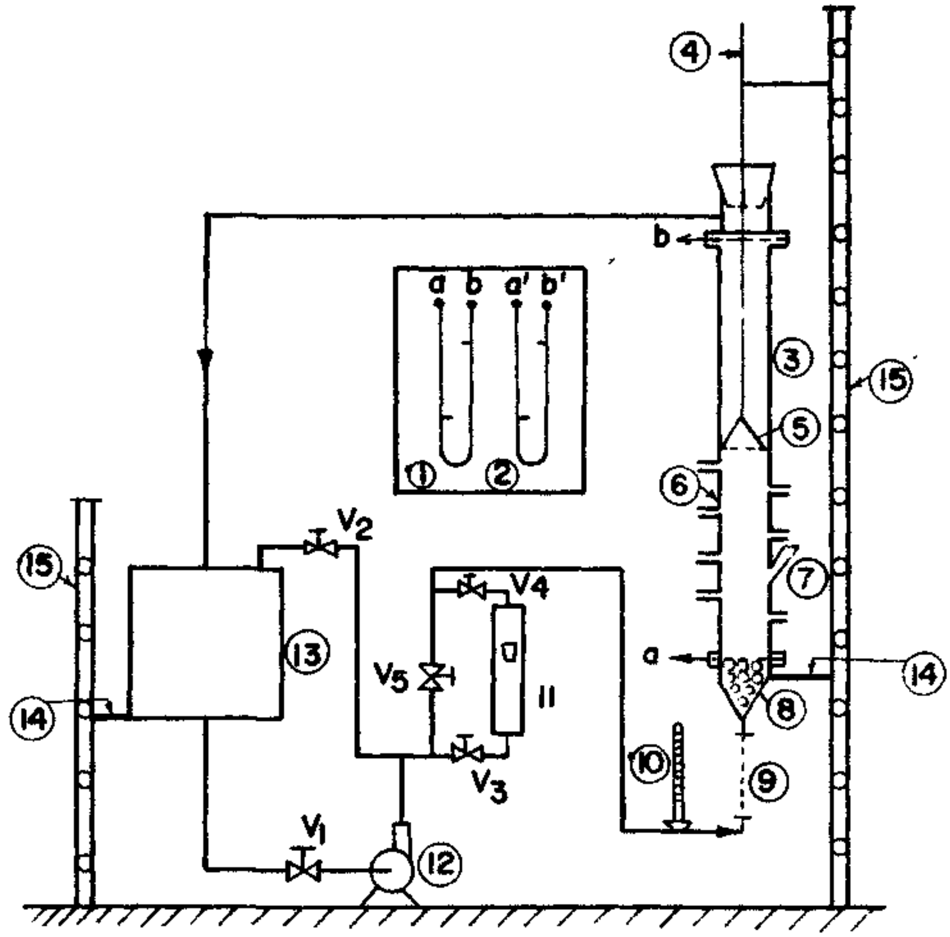
Physical properties of fluids used

Sl. No.	Fluid	Av.temp. ^{o}C	Density gm/cc.	Viscosity cp.	Use
1.	Water	26	1.00	0.874	Semifluidizing medium.
2.	Carbon Tetra-chloride	26	1.63	-	Manometer liquid.
3.	Mercury	26	13.60	-	Manometer liquid.

TABLE- 3.2

Physical properties of materials and ranges of variables studied

Sl. No.	Materials used	Particle size, d_p Mesh No. BSS	Particle size, d_p Cm.	Density gm./cc	Fixed bed porosity, ϵ_{pa}	R	h_s, Cms
1.	Dolomite	6/8	0.2435	2.83	0.470		
2.	Dolomite	14/16	0.1104	2.83	0.351	2.0 2.5 3.0 3.5	6.0 8.0 10.0 12.0
3.	Dolomite	25/30	0.0550	2.83	0.310		
4.	Dolomite	36/44	0.0388	2.83	0.256		
5.	Dolomite	52/60	0.0273	2.83	0.222		
6.	Chromite	14/16	0.1104	3.72	0.500		
7.	Chromite	36/44	0.0388	3.72	0.303		
8.	Baryte	14/16	0.1104	4.45	0.415	2.0 2.5 3.0 3.5	6.0
9.	Baryte	36/44	0.0388	4.45	0.316		
10.	Iron Ore	14/16	0.1104	5.25	0.436		
11.	Iron Ore	36/44	0.0388	5.25	0.304		



1 & 2. MANOMETERS FOR BED PRESSURE DROP
3. SEMIFLUIDIZER
4. MOVABLE RESTRAINT ASSEMBLY
5. TOP RESTRAINT
6. INTERMEDIATE PRESSURE TAPPINGS
7. INCLINED FEEDER
8. DISTRIBUTOR
9. FLEXIBLE CONNECTION
10. THERMOMETER
11. ROTAMETER
12. CIRCULATING PUMP
13. LIQUID RESERVOIR
14. BASE PLATE SUPPORT
15. SUPPORTING STRUCTURE
a, b, COLUMN PRESSURE TAPPINGS
V_1-V_5 CONTROL VALVES

FIG. 3.1 SCHEMATIC DIAGRAM OF THE LIQUID-SOLID SEMI-FLUIDIZATION SET-UP

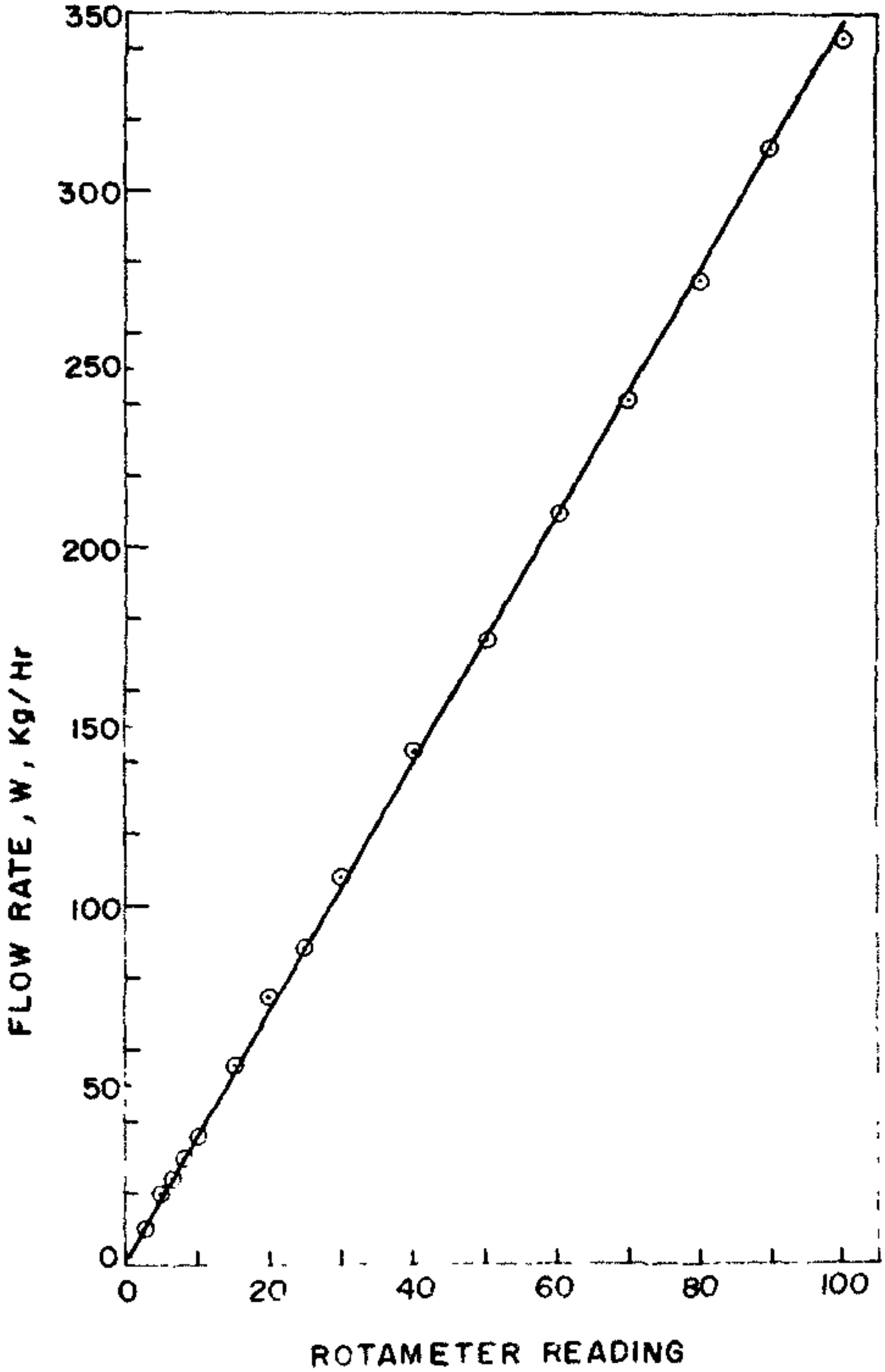


FIG. 3.2 CALIBRATION CHART FOR ROTAMETER

(LOWER RANGE)

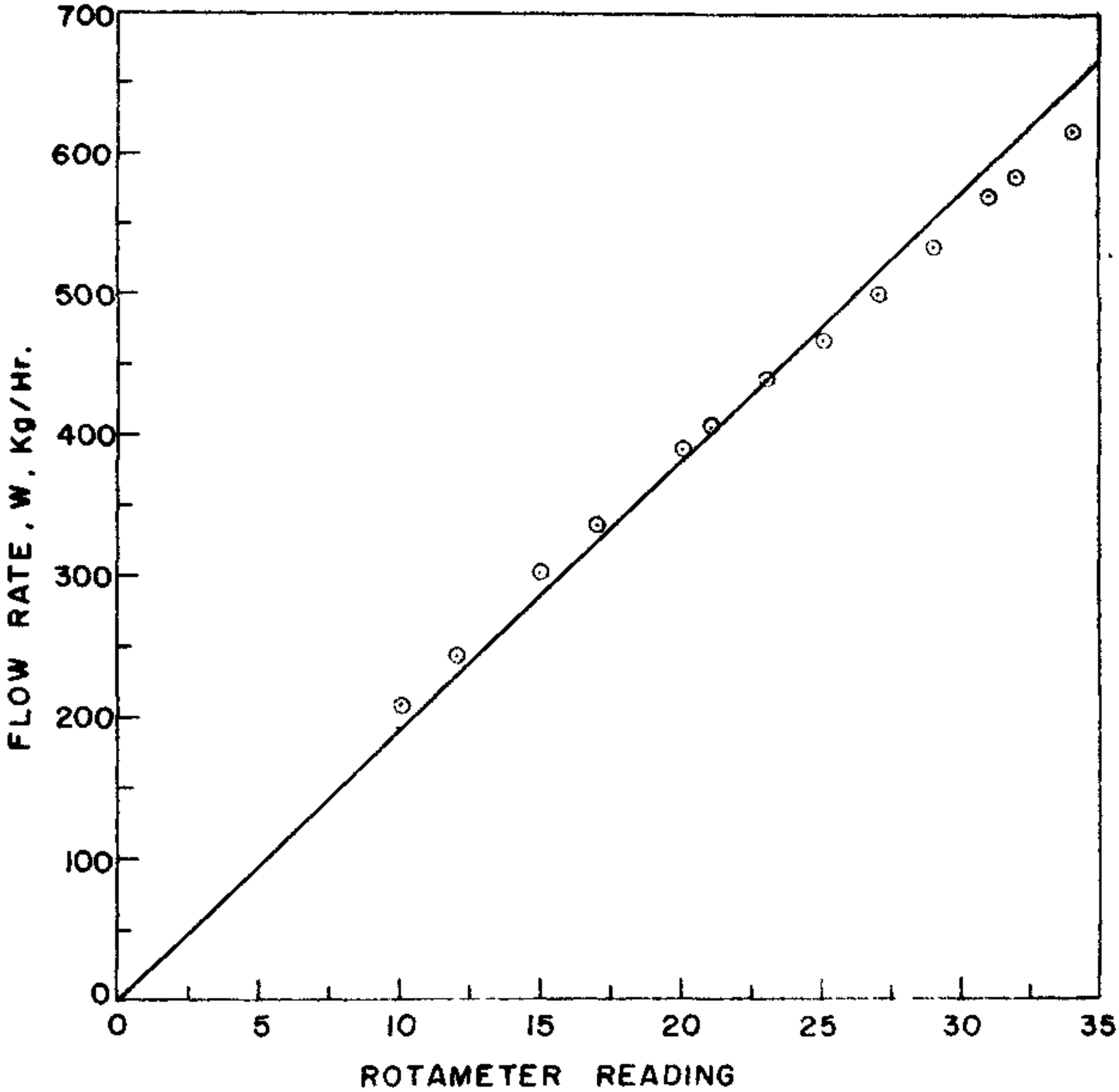


FIG. 3.3 CALIBRATION CHART FOR ROTAMETER (HIGHER RANGE)

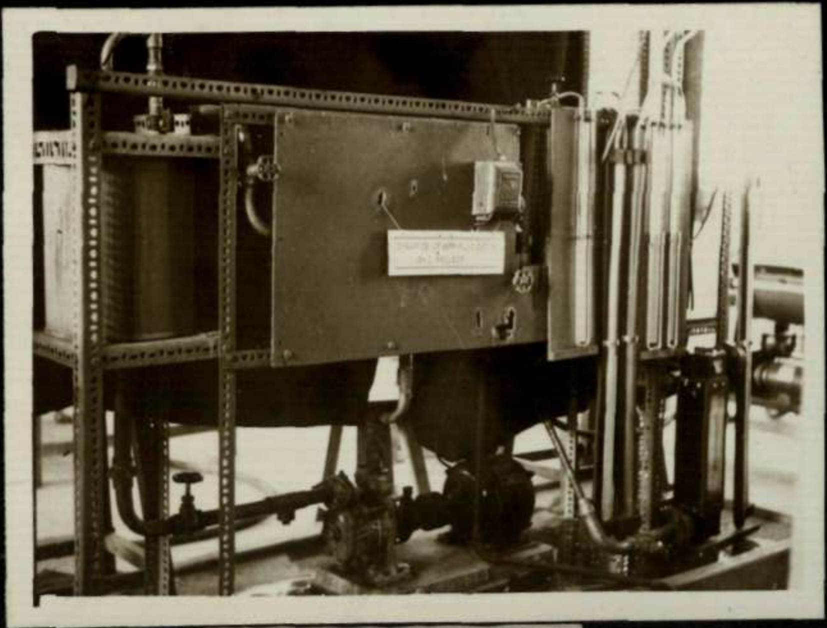


PLATE - 1.A

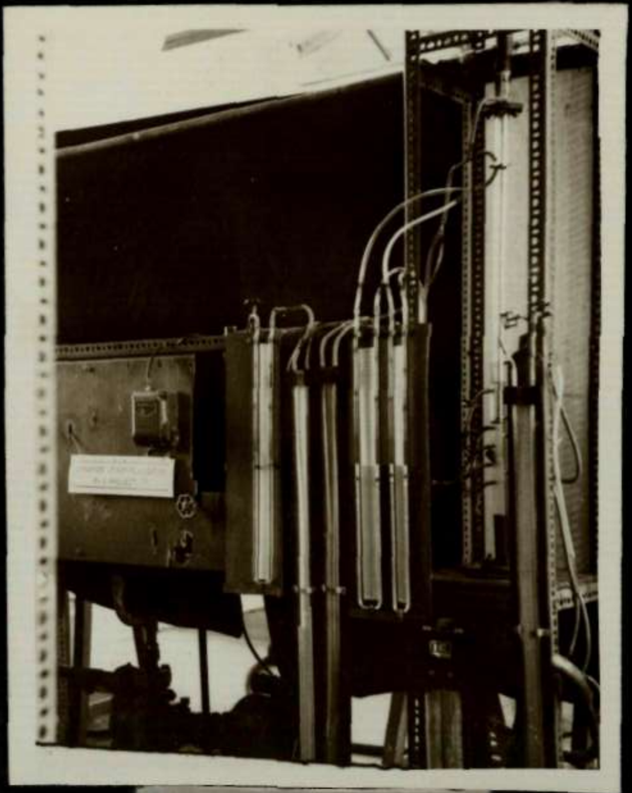


PLATE - 1.B

LIQUID-SOLID SEMI-FLUIDIZATION SET-UP

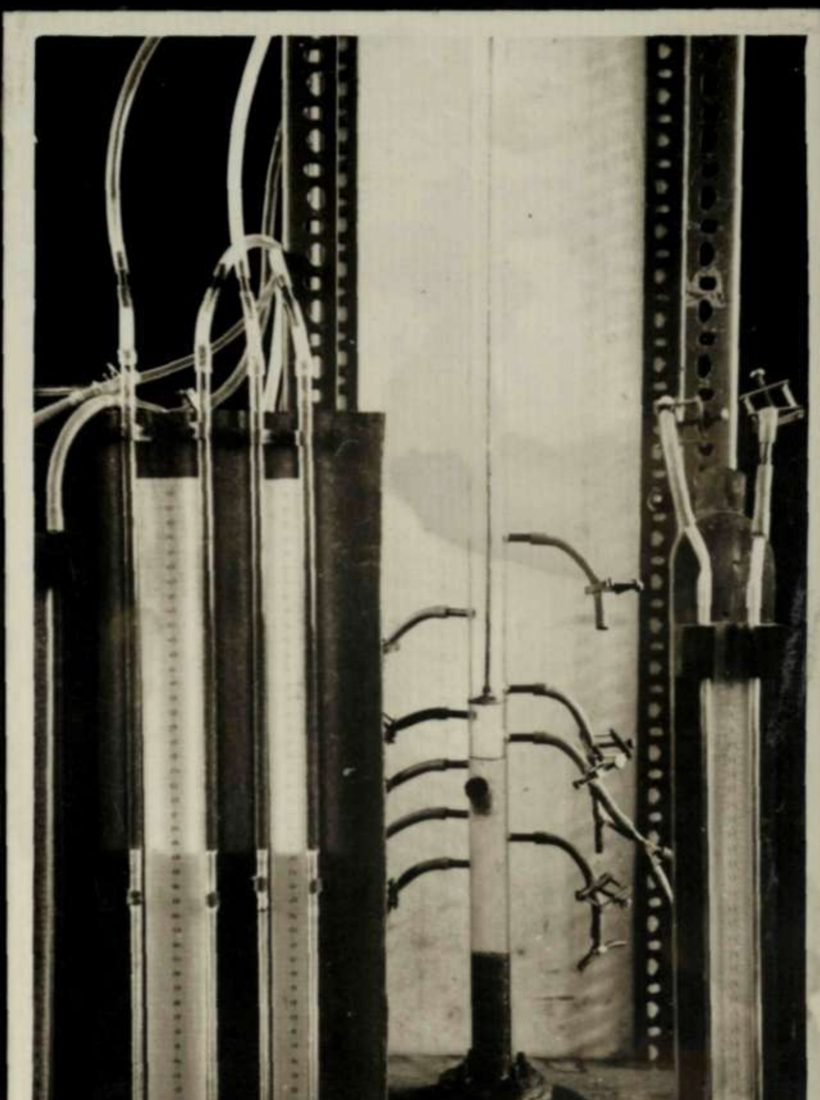


PLATE - 2
LIQUID-SOLID SEMIFLUIDIZER

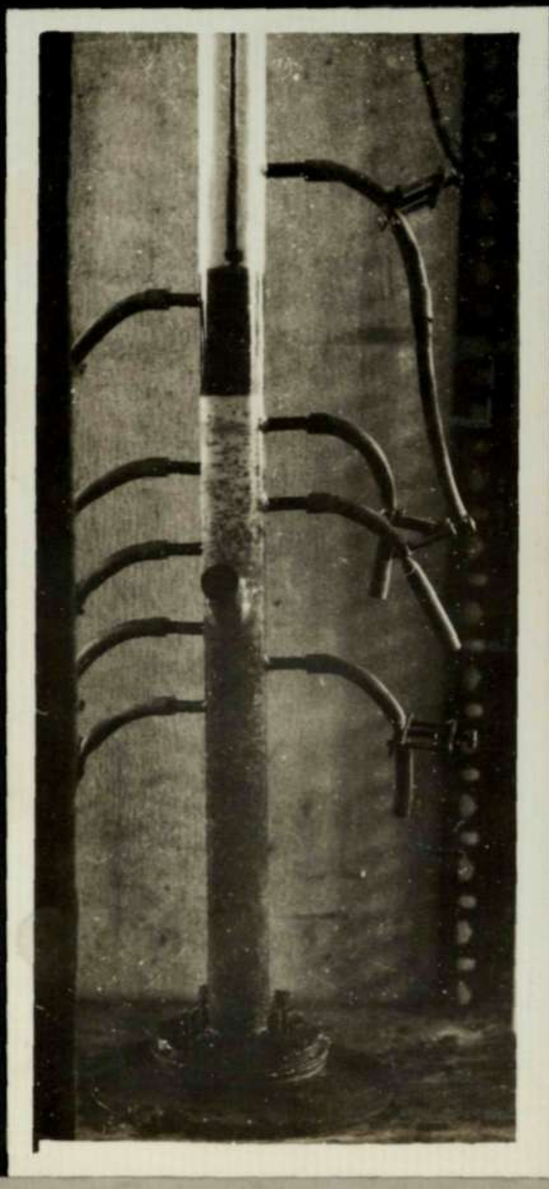


PLATE - 3
A TYPICAL SEMIFLUIDIZED BED

C H A P T E R - IV

EXPERIMENTAL ASPECTS (GAS-SOLID SYSTEM)

EXPERIMENTAL ASPECTS (GAS-SOLID SYSTEM)

EXPERIMENTAL SET-UP:-

The experimental set-up consists primarily of the following components as shown in Fig.4.1 and plate-4.

1. Air compressor :- It is a double-stage air-cooled compressor.

2. Air reservoir (13) :- It is a horizontal cylindrical tank used for ensuring a steady flow of the compressed air. This tank is also provided with a drain valve which is opened periodically for draining of accumulated oil.

3. Drying tower (12) :- A cylinderical mild steel tower packed with silica gel and placed before the semifluidizer to ensure supply of dry air.

4. Orifice-meter (11).

5. Air distributor and calming section (9):- A cylindro-conical section packed with 5 mm diameter glass beds.

6. Semifluidizer (5) :- It is a 4.4 cm. inside diameter and 100 cm. long perspex column fixed to two perspex flanges at both ends. Two pressure tappings are provided in the two flanges for noting the column pressure drop. The grid to support the solids is made up of 60 mesh stainless steel wire net and is placed between the bottom flanges just above the lower pressure tapping. Plate-5 shows the details of the semifluidizer.

7. Movable restraint (7):- The details of the movable restraint are shown in fig. 4.2. It is made up of 60 mesh brass

screen fitted to a truncated plastic cone. In order to make the restraint air-tight, a thin strip of rubber is fixed to the periphery of the cone, The movement of the cone assembly is achieved with the help of a ¼" diameter mild steel rod, held in position by a small nut and bolt arrangement to a top perforated plate attached to the cone. A portion of the rod project to the outside of the column through a hole in a rubber cork fitted to the top. The rod can be fixed with respect to a particular position of the movable restraint by means of a clamp at the top.

8. Manometer panel board (17):- Two sets of manometers are provided, one being used for the measurement of pressure drop in the orificemeter and the other for the bed pressure drop.

9. Thermometer pocket- It is provided for the measurement of temperature of air.

Compressed air from the air reservoir, dried by passing it through a silica gel tower, was used as the semi-fluidizing medium. A calibrated orifice meter was used to measure to the air flow rate. The calibration charts are given in figs. 4.3, 4.4, and 4.5. A set of two manometers with carbon tetrachloride (coloured) and mercury as the manometric liquids, were used to determine the pressure drop across the orificemeter. An identical set measured the column pressure drop. Temperatures of the semifluidizing medium were recorded at the beginning and end of each run and the system properties were evaluated at the average of these two temperatures.

EXPERIMENTAL PROCEDURE :

The various experimental procedures followed in these studies are described below.

1) Determination of fixed bed porosity :-

A semifluidizer of different diameter was used in the studies for the gas- solid system, but the particle sizes were not altered. As a result, it is expected that the wall effect will have influence on the fixed bed porosity. For verification, three samples of materials were taken and the fixed bed porosity was determined for each (by the method described earlier for the liquid- solid systems). The variations in the values were almost negligible and hence the values of fixed bed porosity, determined in the liquid-solid studies, were also used in the present case.

2) Dynamic studies of the semi-fluidization phenomena :-

In the beginning, a blank run was conducted with the bottom grid and the top restraint in position. Pressure drop across the column was measured for the whole range of flow rates maintained during the studies. As the pressure drop was appreciable (table- 5 and fig.- 1 of Appendix- A), these values were subtracted from the overall pressure drop measured in the actual experiments to obtain the actual bed pressure drop.

A sample of material was charged to the column and the fixed bed height was recorded as described earlier. By addition or removal of material from the top, the fixed bed height was adjusted for a desired value. The rubber cork was placed on the top of the column and the position of the movable top restraint was adjusted for a fixed bed expansion ratio. The air flow rate was increased slowly and kept steady for sometime for each reading. Pressure drops across the bed and the orificemeter were carefully recorded, for the fixed, fluidized and semifluidized bed conditions. For the semifluidized bed conditions, the packed bed formations were also recorded accurately. During the run, the reservoir pressure was maintained at 20 psig. and the line pressure (just before entering into the column) at 15 psig. (Plate-6 shows a typical gas-solid semifluidized bed).

After the run was complete the restraint was moved to a new position and the entire process was repeated.

The initial fixed bed height was increased to another definite value by additional amount of material charged from the top and the above procedure was repeated. From the knowledge of liquid-solid semi-fluidization studies, it was observed that the initial static bed height had no appreciable influence on quantities like minimum and maximum semi-fluidization velocities, semifluidized bed pressure drop etc. Hence, for only one system, different values/of initial static bed height were maintained.

III) Bed Expansion studies :-

The procedure adopted here was exactly similar to that followed in case of liquid-solid systems.

Physical properties of the fluids used in experiments are given in table- 4.1 and that of solids along with the ranges of variables studied are given in table- 4.2.

TABLE- 4.1.

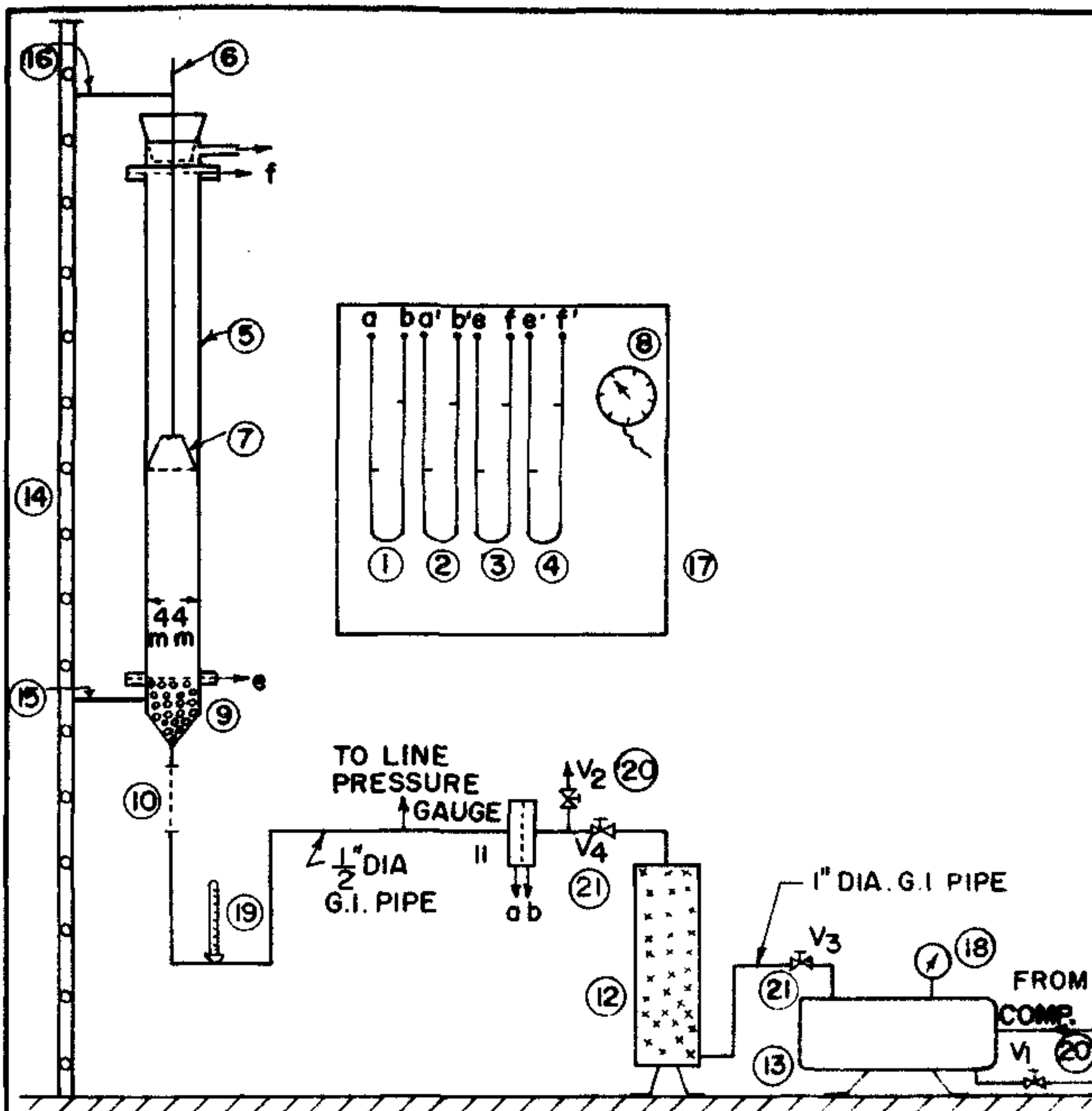
Physical properties of fluids used

Sl. No.	Fluid	Av.temp. ^oC	Density gm/cc.	Viscosity poise	Use
1.	Air	33	0.00234	1.865×10^{-4}	Semifluidizing medium
2.	Carbon Tetra-chloride	33	1.63000	-	Manometer liquid
3.	Mercury	33	13.60000	-	Manometer liquid.

TABLE-4.2

Physical properties of materials and ranges of variables studied

Sl. No.	Materials used	Particle size, d_p Mesh No. BSS	Particle size, d_p Cm.	Density gm./cc	Fixed bed porosity, ϵ_{pa}	R	h_s, Cms
1.	Dolomite	6/8	0.2435	2.83	0.470	2.0, 2.5, 3.0, 3.5	6.0
2.	Dolomite	14/16	0.1104	2.83	0.351		6.0, 8.0, 10.0, 12.0
3.	Dolomite	25/30	0.0550	2.83	0.310		6.0
4.	Dolomite	36/44	0.0388	2.83	0.256		6.0
5.	Chromite	14/16	0.1104	3.72	0.500		6.0
6.	Baryte	14/16	0.1104	4.45	0.415		6.0
7.	Iron Ore	14/16	0.1104	5.25	0.436		6.0

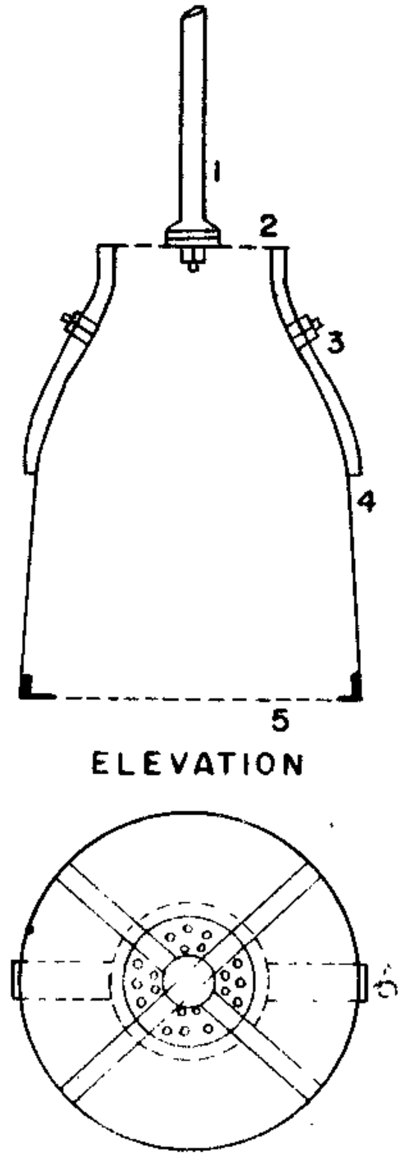


1 & 2. MANOMETERS FOR ORIFICEMETER
3, 4. MANOMETERS FOR BED PRESSURE DROP
5. SEMIFLUIDIZER
6. MOVABLE RESTRAINT ASSEMBLY
7. TOP RESTRAINT
8. LINE PRESSURE GAUGE
9. DISTRIBUTOR
10. FLEXIBLE CONNECTION
11. ORIFICE METER
12. DRYING TOWER
13. RESERVOIR
14. SUPPORTING STRUCTURE
15. BASE PLATE SUPPORT
16. CLAMP
17. PANEL BOARD
18. RESERVOIR PRESSURE GAUGE
19. THERMOMETER
20. V_1, V_2 BY-PASS VALVES
21. V_3, V_4 CONTROL VALVES

a, b. ORIFICE PRESSURE TAPPINGS

e, f – COLUMN PRESSURE TAPPINGS

FIG. 4.1 SCHEMATIC DIAGRAM OF THE GAS-SOLID SEMI-FLUIDIZATION SET-UP.



PLAN (BOTTOM VIEW)

1- MILD STEEL ROD
2- TOP PERFORATED DISC WITH FIXING ARMS
3- FIXING SCREWS
4- TRUNCATED PLASTIC CONE
5- BRASS SCREEN
6- SUPPORTING METAL STRIP

FIG.4.2 DETAILS OF TOP RESTRAINT.

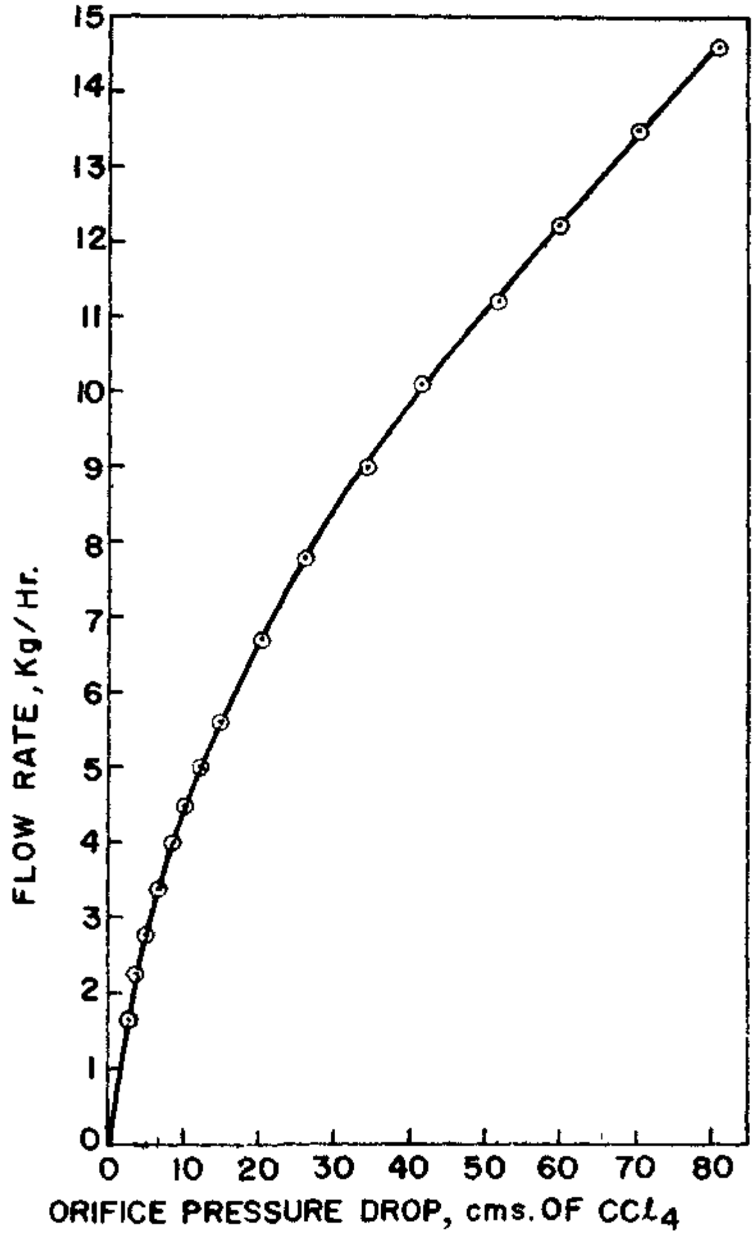


FIG. 4.3 CALIBRATION CHART FOR ORIFICE METER (VERY LOW RANGE)

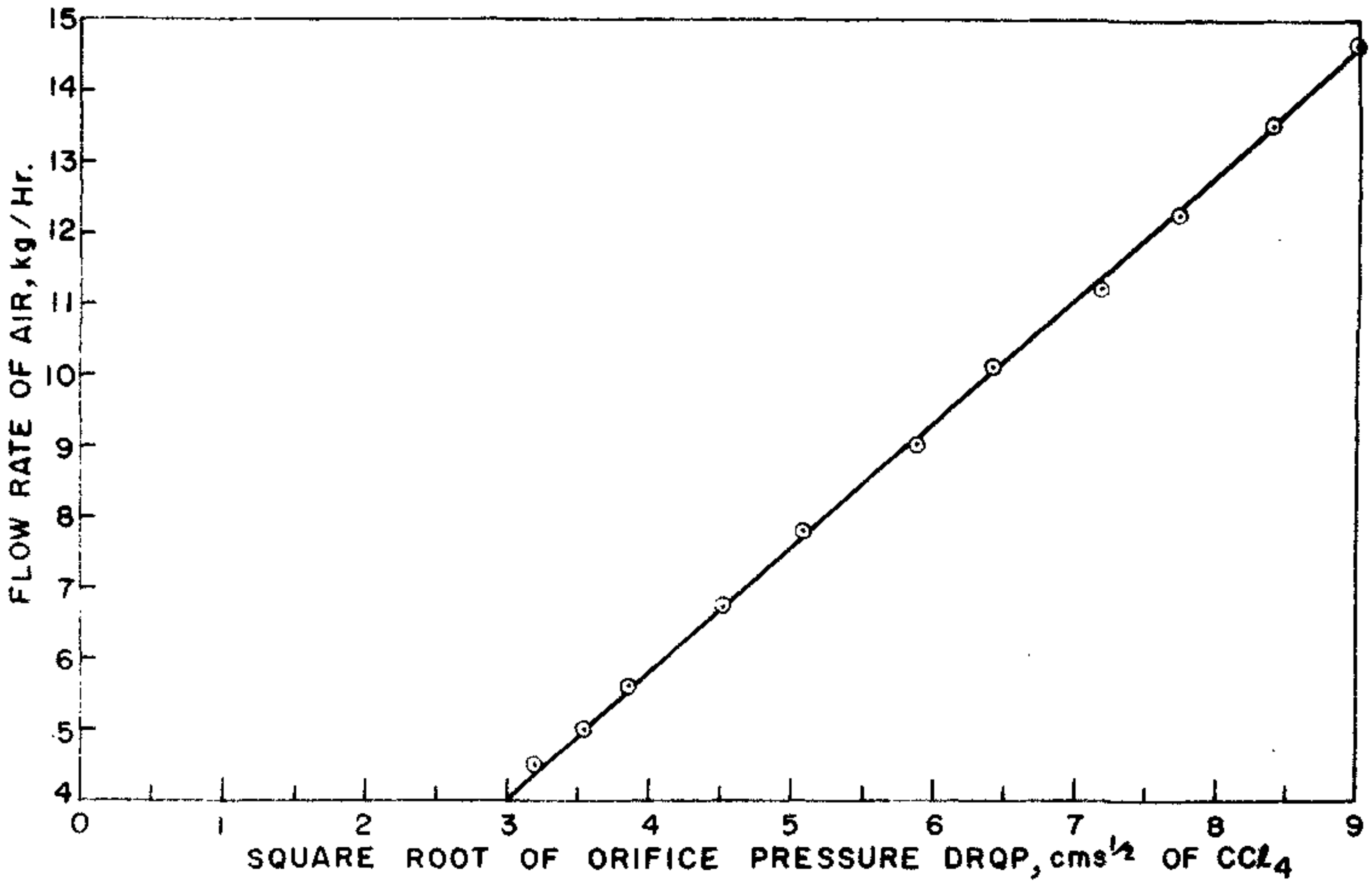


FIG. 4.4 CALIBRATION CHART FOR ORIFICE METER (LOWER RANGE)

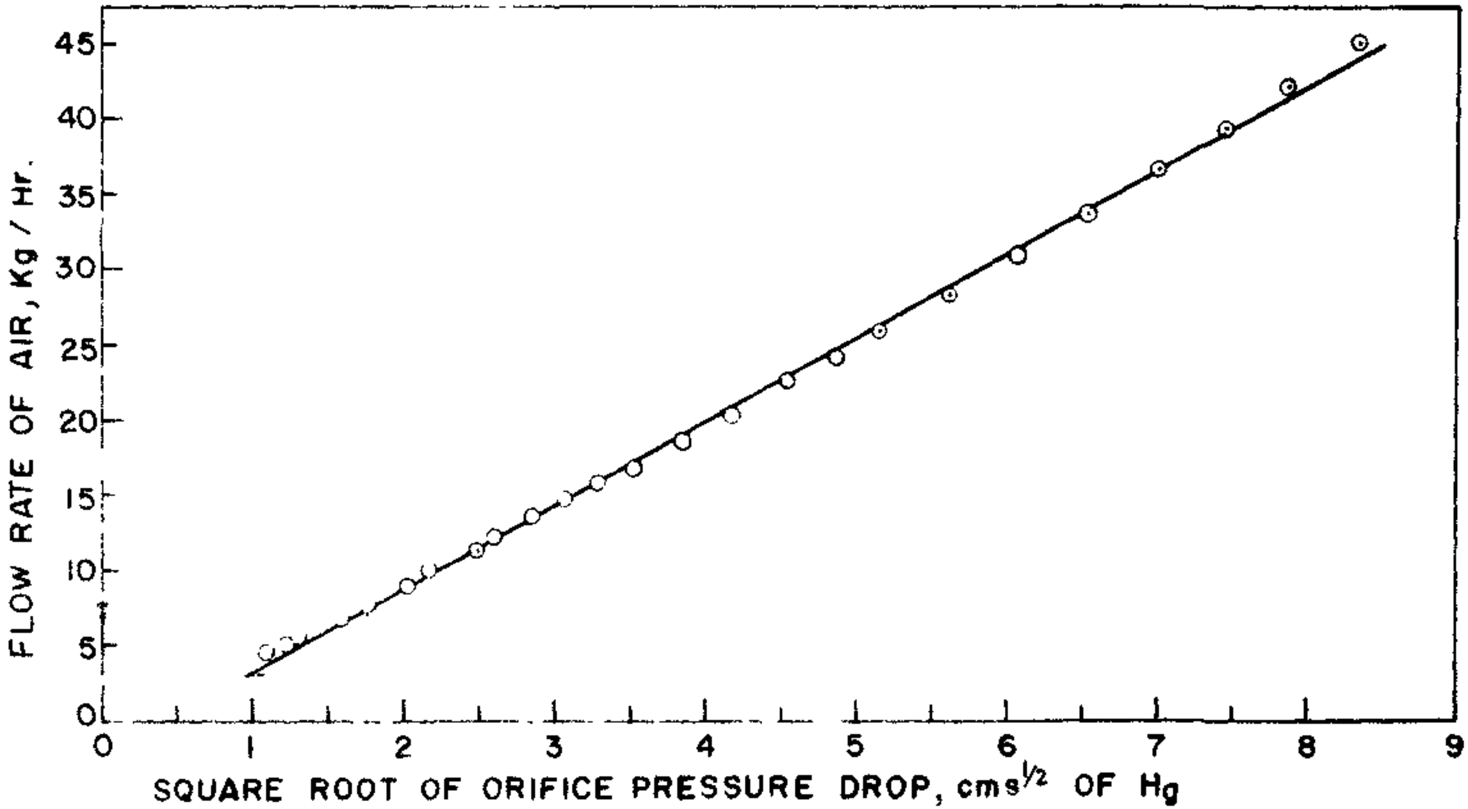


FIG. 4.5 CALIBRATION CHART FOR ORIFICE METER (HIGHER RANGE)

PLATE - 4
GAS-SOLID SEMIFLUIDIZATION SET-UP

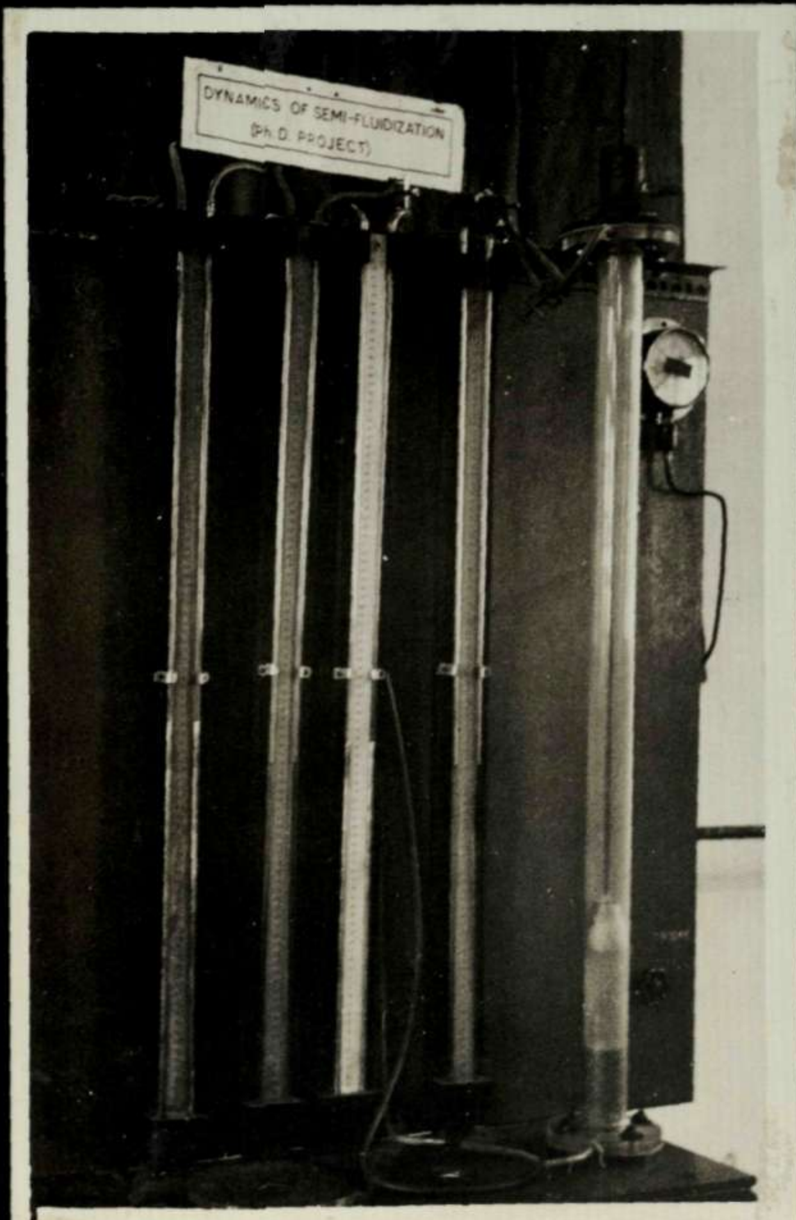


PLATE - 5
GAS-SOLID SEMIFLUIDIZER

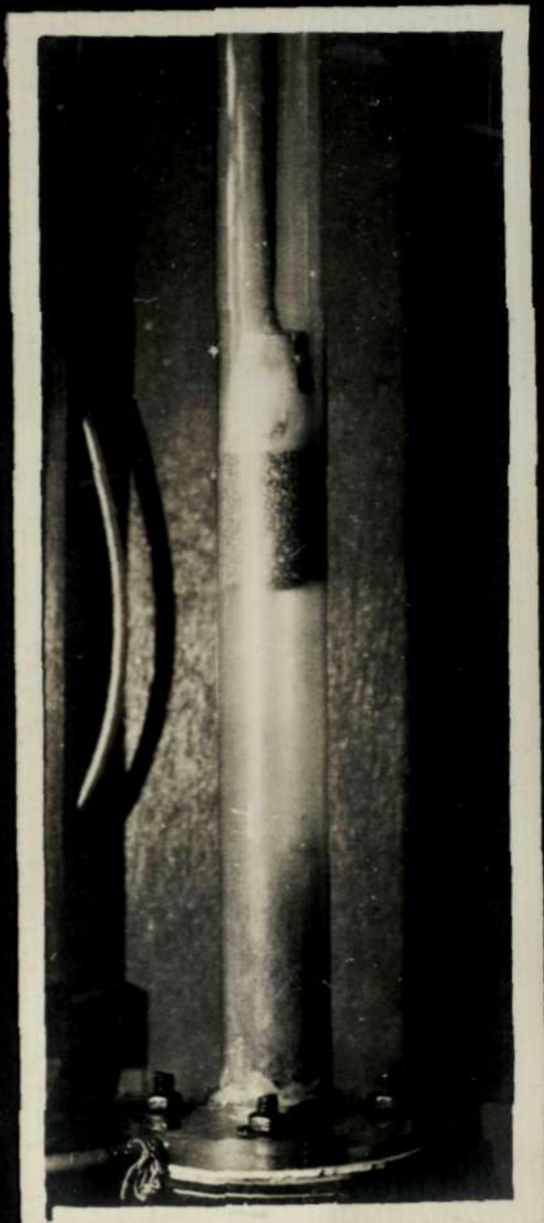


PLATE - 6
A TYPICAL SEMIFLUIDIZED BED

GENERAL NOTATIONS

Throughout the thesis the following notations have been used in specifying run numbers, figures and tables etc.

LSP	Refers to:	liquid-solid system pressure drop data.
LSE	-do-	liquid-solid system bed expansion data.
GSP	-do-	gas-solid system pressure drop data.
GSE	-do-	gas-solid system bed expansion data.
D	=	Dolomite
Cr.	=	Chromite
Ba.	=	Baryte
I	=	Iron ore.
d_{p_1}	=	Particle size of -6 +8 BSS
d_{p_2}	=	Particle size of -14 +16 BSS
d_{p_3}	=	Particle size of -25 +30 BSS
d_{p_4}	=	Particle size of -36 +44 BSS
d_{p_5}	=	Particle size of -52 +60 BSS
h_{s_1}	=	Initial static bed height of 6 Cms.
h_{s_2}	=	Initial static bed height of 8 Cms.
h_{s_3}	=	Initial static bed height of 10 Cms.
h_{s_4}	=	Initial static bed height of 12 Cms.
R_1	=	Semi-fluidization bed expansion ratio of 2.0
R_2	=	Semi-fluidization bed expansion ratio of 2.5
R_3	=	Semi-fluidization bed expansion ratio of 3.0
R_4	=	Semi-fluidization bed expansion ratio of 3.5

All table and figure numbers marked with subscripts 'A' and 'B' refer to liquid-solid and gas-solid systems respectively.

C H A P T E R - V

PREDICTION OF ONSET AND MAXIMUM SEMI-FLUIDIZATION VELOCITIES IN (A) LIQUID-SOLID AND (B) GAS-SOLID SYSTEMS.

** The tables and figures referred in the text have been given at the end of the chapter.

PREDICTION OF ONSET AND MAXIMUM SEMI-FLUIDIZATION VELOCITIES IN (A) LIQUID-SOLID AND (B) GAS-SOLID SYSTEMS

Semi-fluidization characteristics of a bed of particles are dependent on the static and dynamic properties of the system. The static properties include :

(a) Characteristics of particles like size, true density and shape.

(b) Fluid characteristics like density, viscosity and surface tension etc.

(c) Equipment characteristics such as, the height and diameter of fluidizer and position of the movable restraint.

The dynamic properties include mainly the velocity of the fluid stream.

Data on materials used and ranges of studies are given in terms of dimensionless groups in tables - $5.A_1$ and $5.B_1$ for the liquid-solid and gas-solid systems respectively. The experimental data obtained for different particles used in both liquid-solid and gas-solid systems are given in tables- 1 to 115 and tables- 1 - 47 respectively and are included in Appendix- B.

MAXIMUM SEMI-FLUIDIZATION VELOCITY :

This is the velocity of fluid corresponding to which the entire bed of solid particles is transferred upwards to form a packed bed below the top restraint. In actual experiments, very often it is not possible to transfer the entire material to the top. There are two methods[1] for the prediction of the maximum semi-fluidization velocity from extrapolation of the experimental data. These are :

(i) Extrapolation of h_{pa}/h_s value equal to unity from the plot of h_{pa}/h_s vs. G. (figs.5.A_1 to 5.A_4 and 5.B_1 to 5.B_4).

(ii) Extrapolation of ϵ_f vs. G curve to a value of ϵ_f = 1.0 (figs.5.A_5 to 5.A_7 and 5.B_5 and 5.B_6).

The values of the maximum semi-fluidization velocity obtained by the above two methods are given in tables 5.A_2 and 5.B_2 for liquid-solid and gas-solid systems respectively.

It can be observed from the table- 5.A_2 that comparatively higher values of maximum semi-fluidization velocity are obtained by extrapolation of ϵ_f vs. G plots in the case of liquid-solid systems. This can be explained as due to the higher velocity required for keeping the particles under suspension in a fluidized bed without any restraint at the top. However, opposite behaviour has been marked in case of gas-solid systems (table- 5.B_2) where, the values obtained by extrapolation of ϵ_f vs. G plots are comparatively lower in most of the cases. This may be attributed to the fact that, because of the aggregative nature and channelling behaviour of gas-solid systems, at higher fluid velocities, the measured porosity values will be higher than the actual ones and will consequently make the extrapolated values lower.

Correlation :-

For both liquid-solid and gas-solid systems under investigation, it was observed that the effect of initial static bed height and the position of movable restraint on maximum semi-fluidization velocity was not appreciable (Figs. $5.A_1$ - $5.A_2$ and $5.B_1$ - $5.B_2$). The effect of density and particle size on maximum semi-fluidization velocity for liquid-solid and gas-solid systems are given in figs.- $5.A_3$ - $5.A_4$ and $5.B_3$ - $5.B_4$ respectively. It follows that parameters of importance are the particle Reynolds number and the Galileo number. The former takes into account the effect of velocity, whereas the latter represents the physical characteristics of the fluid and the solid. The relation between the dimensionless groups can be written as -

$$Re_{msf} = \varphi(Ga) \qquad \ldots \qquad (5.1)$$

Re_{msf} has been plotted against Galileo number on log-log coordinates in fig.- $5.A_8$ for liquid-solid systems and fig.- $5.B_7$ for the gas-solid systems. All the data can be well represented by a linear relationship which can be written as:

for liquid-solid systems,

$$Re_{msf} = 0.655\ (Ga)^{0.55} \qquad \ldots \qquad (5.2A)$$

for gas-solid systems,

$$Re_{msf} = 0.483\ (Ga)^{0.55} \qquad \ldots \qquad (5.2B)$$

In terms of mass velocity, the above equation simplifies to,

for liquid-solid systems,

$$G_{msf} = 1.85\times10^{4}\ \frac{d_p^{0.65}\left[\rho_f\ (\ \rho_s - \rho_f)\right]^{0.55}}{\mu^{0.10}} \quad \ldots\ (5.3A)$$

for gas-solid systems,

$$G_{msf} = 1.37\times10^{4}\ \frac{d_p^{0.65}\left[\rho_f(\ \rho_s - \rho_f)\right]^{0.55}}{\mu^{0.10}} \quad \ldots\ (5.3B)$$

The values of the maximum semi-fluidization velocity calculated from the above equations have been found to be in good agreement with the experimental data (table Nos.5.A_3 and 5.B_3). The percentage deviation lies within $\pm$ 10% for liquid-solid systems and $\pm$ 5% for the gas-solid systems.

MINIMUM SEMI-FLUIDIZATION VELOCITY :-

The velocity corresponding to which the first particle of the bed touches the top restraint of the semifluidizer is called the minimum semi-fluidization velocity. In an actual experiment it is not possible to visualize this situation exactly. Hence the value of minimum semi-fluidization velocity is to be obtained indirectly. When the pressure drop across a bed is plotted against fluid mass velocity on log-log coordinates, two distinct breaks are observed for the curve. These two points corresponding to the change of slopes indicate the onset of fluidization (G_{mf}) and the onset of semi-fluidization (G_{osf}) velocities, in order of occurrence. In the present case, the values of G_{osf} as obtained from plots of ΔP_T vs. G (fig.5.A_9 - 5.A_{12} and 5.B_8 - 5.B_{11}) are given in tables 5.A_4 - 5.A_5 and 5.B_4 - 5.B_5 for the liquid-solid and the gas-solid systems respectively.

An alternative method of obtaining the minimum semi-fluidization velocity is to use expanded bed data. In the h_f/h_s vs. G plots (fig. 5.A_{13} - 5.A_{15} and 5.B_{12} - 5.B_{13}), the fluid velocity corresponding to h_f/h_s = R, represents the minimum semi-fluidization velocity. The values from expanded bed data, are given in tables 5.A_6 and 5.B_6. These values of minimum semi-fluidization velocity, when compared with the same obtained from ΔP_T vs. G plots, indicate higher values. This is because an accurate measurement of expanded bed height in fluidized state presents considerable difficulty.

<u>Correlation</u> :-

The parameters of importance for this case are, G_{osf}/G_{msf}, h_s/D_c, D_c/d_p, ρ_s/ρ_f and R. The relation between the group G_{osf}/G_{msf} and the other parameters can be written in the following manner :

$$\frac{G_{osf}}{G_{msf}} = \frac{h_s}{D_c}, \frac{D_c}{d_p}, \quad \frac{\rho_s}{\rho_f}, R \qquad \ldots \qquad (5.4)$$

It has been observed that the static bed height has no appreciable effect on the onset of semi-fluidization velocity. (tables - 5.A_4 and 5.B_4, figs. 5.A_9 and 5.B_8). As a result, an average value of semi-fluidization velocity (minimum) at a particular bed expansion ratio can be used irrespective of the static bed height (table 5.A_5 and 5.B_5). Since for the system under study only one column has been used, effect of h_s/D_c group is not relevant and hence, the expression (5.4) reduces to -

$$\frac{G_{osf}}{G_{msf}} = A \left(\frac{D_c}{d_p}\right)^{a_1} \left(\frac{\rho_s}{\rho_f}\right)^{a_2} (R)^{a_3} \qquad \ldots \qquad (5.5)$$

where, A is a constant and a_1, a_2 and a_3 are respective exponents of the system variables.

Effect of individual parameters on G_{osf}/G_{msf} :-

(i) Effect of D_c/d_p -

Performance of a semifluidizer depends upon the wall effect i.e., D_c/d_p ratio. From figs. 5.A_{10} and 5.B_9 it follows that the minimum semi-fluidization velocity is higher in case of coarser particles and in order to study this effect on G_{osf}/G_{msf}, plots of G_{osf}/G_{msf} against D_c/d_p have been made and straight lines have been obtained. The slopes are -0.367 and -0.292 respectively for the liquid-solid and gas-solid systems. This indicates that, for higher value of D_c/d_p, the velocity ratio will decrease. In other words, finer the particle size, lower will be the ratio of onset to maximum semi-fluidization velocity for a particular semifluidizer.

(ii) Effect of density ratio (ρ_s/ρ_f) -

Both drag and buoyant forces are responsible for upward particle movement and will depend on a number of variables including the density ratio. Since the uplifting of the particle is to be achieved by a fluid having a different density, the particle would undergo relative displacement during forward and backward motion. The extent of back-mixing, which is a function of particle density, affects the particle equilibrium and hence the velocity ratio. From ΔP_T vs. G plots for the liquid-solid (fig. 5.A_{11}) and the gas-solid systems (fig.- 5.B_{10}), it can be seen that higher the density of the material higher will be onset of semi-fluidization velocity. In order to quantitatively study this effect, plots of G_{osf}/G_{msf} vs. ρ_s/ρ_f were prepared and straight lines of slope 0.288 (for liquid-solid system) and 0.248 (gas-solid system) were obtained. It can be concluded that an increase in the density ratio will lead to a higher mass velocity ratio in semi-fluidization.

(iii) Effect of bed expansion ratio (R) -

In case of semi-fluidization, the bed expansion ratio is of immense importance. The effect of bed expansion ratio has been shown in figs. 5.A_{12} and 5.B_{11} wherefrom it can be concluded that with an increase in the bed expansion ratio, the onset velocity of semi-fluidization increases. Since for a particular fluid-solid system of fixed particle size, the maximum velocity of semi-fluidization remains constant, the velocity ratio becomes a direct function of the bed expansion ratio. This effect has been studied for both liquid-solid and gas-solid cases and straight lines of slopes of 0.655 and 0.561 respectively have been obtained for

G_{osf}/G_{msf} vs. R plots. This is a clear indication of the fact that, an increase in bed expansion ratio will increase the mass velocity ratio and in turn, the onset of semi-fluidization velocity.

After substituting the exponents of the system variables, the equations becomes,

for liquid-solid system -

$$\frac{G_{osf}}{G_{msf}} = A \left[\left(\frac{D_c}{d_p}\right)^{-0.367} \left(\frac{\rho_s}{\rho_f}\right)^{0.288} (R)^{0.655} \right]^{B} \qquad (5.6A)$$

and for gas-solid system,

$$\frac{G_{osf}}{G_{msf}} = A' \left[\left(\frac{D_c}{d_p}\right)^{-0.292} \left(\frac{\rho_s}{\rho_f}\right)^{0.248} (R)^{0.561} \right]^{B'} \qquad (5.6B)$$

where, A and A' are the coefficients and B and B' the exponents of the overall product (Prod.) which acts as a correlation factor for the exponents of the system variables. Hence, the equation can be written as -

$$\frac{G_{osf}}{G_{msf}} = A\ (\text{Prod.})^{B} \qquad \ldots \qquad (5.7)$$

The tables $5.A_7$ - $5.A_9$ and $5.B_7$ - $5.B_9$ give calculated values of the velocity ratio, the effect of individual parameters and the product (Prod.).

In figs. $5.A_{16}$ and $5.B_{14}$, the ratio of G_{osf}/G_{msf} is plotted on log-log coordinates against the products The data can be well represented by straight lines, the equations for which are given as follows:

for liquid-solid systems,

$$\frac{G_{osf}}{G_{msf}} = 0.473 \left[\left(\frac{D_c}{d_p}\right)^{-0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38} \right] \quad (5.8A)$$

and for gas-solid systems,

$$\frac{G_{osf}}{G_{msf}} = 0.071 \left[\left(\frac{D_c}{d_p}\right)^{-0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38} \right] \quad (5.8B)$$

As can be seen from above, the values of the exponents of the groups are same for both the systems with only change of coefficients. Excepting a few cases, the deviations lie within $\pm$ 15 % (tables- $5.A_{10}$ and $5.B_{10}$).

Thus it can be seen that the two correlations presented above are very useful in predicting the onset of semi-fluidization velocity and the maximum semi-fluidization velocity from a knowledge of the system parameters. Since the range of variables studied is large, the equations can be of generalised useage.

REFERENCE

1. Fan, L.T. and Wen, C.Y., A.I.Ch.E. Jl. 7, 606, (1961)

NOMENCLATURE

d_p = Particle diameter, L

D_c = Diameter of the column, L

G = Mass velocity of fluid, $ML^{-2}\theta^{-1}$

Ga = Galileo number, dimensionless group,

$$\frac{d_p^3 \ \rho_f \ (\rho_s - \rho_f) \ g}{\mu^2}$$

G_{mf} = Minimum fluidization mass velocity, $ML^{-2}\theta^{-1}$

G_{msf} = Maximum semi-fluidization mass velocity, $ML^{-2}\ \theta^{-1}$

G_{osf} = Minimum semi-fluidization mass velocity, $ML^{-2}\ \theta^{-1}$

h = Overall height of column (or semifluidized bed) L

h_f Height of fully fluidized bed, L

h_{pa} = Height of packed section in semi-fluidization, L

h_s = Height of initial static bed, L

R = Bed expansion ratio in semi-fluidization dimentionless, h/h_s

Re_{msf} = Particle Reynolds number corresponding to maximum semi-fluidization condition, $\frac{d_p\ G_{msf}}{\mu}$

Φ ψ = Function

ρ_s = Density of solid, ML^{-3}

ρ_f = Density of fluid, ML^{-3}

μ = Viscosity of fluid, $ML^{-1}\theta^{-1}$

ϵ_f = Porosity of fluidized bed dimensionless.

TABLE- 5.A_1

Calculated values of dimensionless groups

Sl. No.	System	particle size, d_p m	Re_{msf}	Ga	Ar
1.	Dolomite-water	0.002435	630.0	$3.395x10^5$	$9.6x10^5$
2.	-do-	0.001104	218.0	$3.180x10^4$	$0.9x10^5$
3.	-do-	0.000550	68.1	$3.910x10^3$	$1.108x10^4$
4.	-do-	0.000388	38.2	$1.375x10^3$	$0.389x10^4$
5.	-do-	0.000273	19.5	$4.805x10^2$	$0.136x10^4$
6.	Chromite- water	0.001104	246.0	$4.725x10^4$	$1.758x10^5$
7.	-do-	0.000388	39.4	$2.042x10^3$	$0.76x10^4$
8.	Baryte- water	0.001104	281.0	$5.990x10^4$	$2.665x10^5$
9.	-do-	0.000388	48.1	$2.590x10^3$	$1.152x10^4$
10.	Iron Ore-water	0.001104	342.5	$7.380x10^4$	$3.875x10^5$
11.	-do-	0.000388	55.5	$3.195x10^3$	$1.677x10^4$

TABLE- 5.B_1

Calculated values of dimensionless groups

Sl. No.	System	Particle size, d_p m	Re_{msf}	Ga	Ar
1	Dolomite-air	0.002435	1560.0	2.685×10^6	3.250×10^9
2	-do-	0.001104	460.5	2.520×10^5	3.045×10^8
3	-do-	0.000550	139.2	3.100×10^4	3.745×10^7
4	-do-	0.000388	80.9	1.090×10^4	1.318×10^7
5	Chromite- air	0.001104	526.0	3.310×10^5	5.255×10^8
6	Baryte- air	0.001104	592.0	3.955×10^5	7.520×10^8
7	Iron Ore- air	0.001104	658.0	4.665×10^5	1.048×10^9

TABLE- $5.A_2$

Experimental maximum semi-fluidization velocities.

Sl. No.	System	d_p m	G_{msf} (From h_{pa}/h_s vs. G curves for $\frac{h_{pa}}{h_s} = 1.0$)	Kg./Hr.M^2 (From ϵ_f vs. G curve for $\epsilon_f = 1.0$)
1	2	3	4	5
1.	Dolomite- water	0.002435	815000	930000
2.	/do/	0.001104	620000	740000
3.	/do/	0.000550	390000	425000
4.	/do/	0.000388	310000	345000
5.	/do/	0.000273	225000	280000
6.	Chromite- water	0.001104	700000	910000
7.	/do/	0.000388	320000	400000
8.	Baryte- water	0.001104	800000	970000
9.	/do/	0.000388	390000	425000
10.	Iron ore- water	0.001104	975000	1000000
11.	/do/	0.000388	450000	500000

TABLE- 5.B2

Experimental maximum semi-fluidization velocities

Sl. No.	System	d_p m	G_{msf}, Kg./Hr.M^2 (From $\frac{h_{pa}}{h_s}$ vs. G curves for $\frac{h_{pa}}{h_s} = 1.0$)	G_{msf}, Kg./Hr.M^2 (From ϵ_f vs. G curves for $\epsilon_f = 1.0$)
1.	Dolomite- air	0.002435	43000	36000
2.	-do-	0.001104	28000	28000
3.	-do-	0.000550	17000	20600
4.	-do-	0.000388	14000	19400
5.	Chromite- air	0.001104	32000	31200
6.	Baryte- air	0.001104	36000	34400
7.	Iron Ore- air	0.001104	40000	36000

TABLE- 5.A3

Comparison of the maximum semifluidization velocities.

Sl. No.	System	d_p, m	G_{msf}, Kg/Hr.M^2 Experimental (for $\frac{h_{pa}}{h_s} = 1$)	Calculated (by equation)	Percentage deviation of calculated values from the experimental
1.	Dolomite-water	0.002435	815000	924070	+ 13.38
2.	-do-	0.001104	620000	551780	- 11.00
3.	-do-	0.000550	390000	350870	- 10.03
4.	-do-	0.000388	310000	279310	- 9.90
5.	-do-	0.000273	225000	222330	- 1.19
6.	Chromite-water	0.001104	700000	685300	- 2.10
7.	-do-	0.000388	320000	346890	+ 8.40
8.	Baryte-water	0.001104	800000	781690	- 2.29
9.	-do-	0.000388	390000	395680	+ 1.46
10.	Iron ore-water	0.001104	975000	879840	- 9.76
11.	-do-	0.000388	450000	445370	- 1.03

TABLE- 5.B3

Comparison of the maximum semi-fluidization velocities

Sl. No.	System	d_p m	G_{msf}, Kg/Hr.M^2 experimental (for $\frac{h_{pa}}{h_s} = 1$)	G_{msf}, Kg/Hr.M^2 Calculated by equation	Percentage deviation of calculated values from the experimental
1.	Dolomite- air	0.002435	43000	46050	+ 7.10
2.	-do-	0.001104	28000	27700	- 1.07
3.	-do-	0.000550	17000	17570	+ 3.35
4.	-do-	0.000388	14000	13980	- 0.14
5.	Chromite- air	0.001104	32000	31800	- 0.62
6.	Baryte- air	0.001104	36000	35050	- 2.64
7.	Iron Ore- air	0.001104	40000	38750	- 3.13

T A B L E- 5.A_4

Experimental minimum semi-fluidization velocities.

Sl. No.	System	Bed height h_s, cms.	Minimum semi-fluidization velocities at various bed expansion ratios, (R) Kg./Hr.M^2			
			R=2.0	R=2.5	R=3.0	R=3.5
		Effect of particle size				
1.	Dolomite-water (6/8 BSS)	6.0	420000	490000	520000	540000
		8.0	420000	495000	525000	540000
		10.0	410000	480000	520000	550000
		12.0	410000	480000	515000	550000
2.	Dolomite-water (14/16 BSS)	6.0	210000	240000	290000	310000
		8.0	220000	250000	300000	320000
		10.0	225000	250000	290000	320000
		12.0	210000	250000	300000	320000
3.	Dolomite-water (25/30 BSS)	6.0	115000	140000	155000	178000
		8.0	110000	140000	152000	180000
		10.0	115000	137000	162000	178000
		12.0	115000	145000	165000	182000
4.	Dolomite-water (36/44 BSS)	6.0	75000	96000	105000	120000
		8.0	75000	95000	105000	120000
		10.0	78000	95000	110000	120000
		12.0	80000	97000	110000	120000
5.	Dolomite-water (52/60 BSS)	6.0	50000	67000	76000	87000
		8.0	50000	66000	76000	87000
		10.0	53000	67000	78000	88000
		12.0	55000	69000	78000	88000

Table-5.A_4 (contd.)

Experimental minimum semi-fluidization velocities.

Sl. No.	System	Bed height h_s, cms.	Minimum semi-fluidization velocities at various bed expansion ratios, (R) Kg./Hr.M^2			
			R=2.0	R=2.5	R=3.0	R=3.5
	Effect of Density of Materials					
6.	Chromite-water (14/16 BSS)	6.0	275000	325000	370000	405000
7.	Baryte-water (14/16 BSS)	6.0	300000	350000	400000	440000
8.	Iron ore-water (14/16 BSS)	6.0	390000	440000	500000	550000
9.	Chromite-water (36/44 BSS)	6.0	108000	130000	145000	155000
10.	Baryte-water (36/44 BSS)	6.0	130000	155000	175000	195000
11.	Iron ore-water (36/44 BSS)	6.0	140000	175000	200000	220000

T A B L E- 5.A_5

Average value of minimum semi-fluidization velocities (experimental)

Sl. No.	System	Particle size d_p, m	Average value of minimum semi-fluidization velocity at various bed expansion ratios, (R) Kg./Hr.M^2			
			R=2.0	R=2.5	R=3.0	R=3.5
1.	Dolomite-water	0.002435	415000	486250	520000	545000
2.	-do-	0.001104	216250	247500	295000	317500
3.	-do-	0.000550	113750	140500	158500	179500
4.	-do-	0.000388	77000	95500	107500	120000
5.	-do-	0.000273	52000	67250	77000	87500
6.	Chromite-water	0.001104	275000	325000	370000	405000
7.	-do-	0.000388	108000	130000	145000	155000
8.	Baryte-water	0.001104	300000	350000	400000	440000
9.	-do-	0.000388	130000	155000	175000	195000
10.	Iron ore-water	0.001104	390000	440000	500000	550000
11.	-do-	0.000388	140000	175000	200000	220000

TABLE - 5.B4

Experimental Minimum semi-fluidization velocities.

Sl. No.	Systems	Bed height h_s, cms.	Minimum semi-fluidization velocities at various bed expansion ratios, (R) Kg./Hr.M^2			
			R=2.0	R=2.5	R=3.0	R=3.5
	Effect of particle size					
1.	Dolomite- air (6/8 BSS)	6.0	7500	8000	8500	9000
2.	Dolomite- air (14/16 BSS)	6.0	4100	4400	5000	5500
		8.0	3900	4400	4700	5300
		10.0	3900	4200	4600	5300
		12.0	3900	4200	4600	5000
3.	Dolomite- air (25/30 BSS)	6.0	2200	2600	3000	3500
4.	Dolomite-air (36/44 BSS)	6.0	1550	1650	2200	2500
	Effect of Density of Materials					
5.	Chromite- air (14/16 BSS)	6.0	5000	5800	6300	6800
6.	Baryte- air (14/16 BSS)	6.0	5500	5900	6500	7000
7.	Iron Ore- air (14/16 BSS)	6.0	6400	6900	7500	8000

TABLE- 5.B5

Average value of minimum semi-fluidization velocities (experimental)

Sl. No.	System	Particle size d_p, m	Average value of minimum semi-fluidization velocities at various bed expansion ratios, (R) Kg./Hr.M^2			
			R=2.0	R=2.5	R=3.0	R=3.5
1.	Dolomite- air	0.002435	7500	8000	8500	9000
2.	-do-	0.001104	3950	4300	4725	5275
3.	-do-	0.000550	2200	2600	3000	3300
4.	-do-	0.000388	1550	1650	2200	2500
5.	Chromite- air	0.001104	5000	5800	6300	6800
6.	Baryte- air	0.001104	5500	5900	6500	7000
7.	Iron Ore- air	0.001104	6400	6900	7500	8000

TABLE- 5.A_6

Experimental minimum semi-fluidization velocities.
(From expanded bed data)

Sl. No.	System	Particle size d_p, m	Minimum semi-fluidization velocities at various bed expansion ratios (R) Kg./Hr.M^2 R=2.0	R=2.5	R=3.0	R=3.5
1.	Dolomite-water	0.002435	445000	520000	580000	635000
2.	-do-	0.001104	224000	275000	310000	342000
3.	-do-	0.000550	115000	145000	168000	187000
4.	-do-	0.000388	80000	104000	120000	132000
5.	-do-	0.000273	47500	65000	78000	86000
6.	Chromite-water	0.001104	280000	340000	378000	415000
7.	-do-	0.000388	102000	126000	150000	166000
8.	Baryte-water	0.001104	309000	378000	435000	480000
9.	-do-	0.000388	116000	145000	172000	195000
10.	Iron ore-water	0.001104	395000	478000	540000	595000
11.	-do-	0.000388	140000	180000	205000	220000

TABLE- 5.B_6

Experimental minimum semi-fluidization velocities (from expanded bed data)

Sl. No.	System	d_p m	Minimum semi-fluidization velocities at various bed expansion ratios, (R) Kg./Hr.M^2			
			R=2.0	R=2.5	R=3.0	R=3.5
1.	Dolomite- air	0.002435	11200	13300	15100	17000
2.	-do-	0.001104	6550	8700	10800	12500
3.	-do-	0.000550	4000	5450	6800	8100
4.	-do-	0.000388	2850	4050	5400	6450
5.	Chromite- air	0.001104	7600	9800	11900	13800
6.	Baryte- air	0.001104	8200	10700	12700	14500
7.	Iron ore- air	0.001104	9500	11800	13500	15200

TABLE- 5.A_7

Ratio of minimum to maximum semi-fluidization velocity (experimental)

Sl. No.	System	d_p m	G_{msf} Kg./Hr.M^2	R	G_{osf} Kg./Hr.M^2	G_{osf}/G_{msf}
1	2	3	4	5	6	7
1.	Dolomite-water	0.002435	815000	2.0	415000	0.509
				2.5	486250	0.597
				3.0	520000	0.638
				3.5	545000	0.669
2.	-do-	0.001104	620000	2.0	216250	0.349
				2.5	247500	0.399
				3.0	295000	0.475
				3.5	317500	0.512
3.	-do-	0.000550	390000	2.0	113750	0.2915
				2.5	140500	0.360
				3.0	158500	0.406
				3.5	179500	0.460
4.	-do-	0.000388	310000	2.0	77000	0.248
				2.5	95500	0.308
				3.0	107500	0.347
				3.5	120000	0.387
5.	-do-	0.000273	225000	2.0	52000	0.231
				2.5	67250	0.299
				3.0	77000	0.342
				3.5	87500	0.389

T A B L E-5.A_7 (Contd.)

1	2	3	4	5	6	7
6.	Chromite-water	0.001104	700000	2.0	275000	0.393
				2.5	325000	0.465
				3.0	370000	0.529
				3.5	405000	0.579
7.	-do-	0.000388	320000	2.0	108000	0.338
				2.5	130000	0.406
				3.0	145000	0.453
				3.5	155000	0.485
8.	Baryte-water	0.001104	800000	2.0	300000	0.375
				2.5	350000	0.437
				3.0	400000	0.500
				3.5	440000	0.550
9.	-do-	0.000388	390000	2.0	130000	0.333
				2.5	155000	0.398
				3.0	175000	0.449
				3.5	195000	0.500
10.	Iron ore-water	0.001104	975000	2.0	390000	0.400
				2.5	440000	0.451
				3.0	500000	0.513
				3.5	550000	0.564
11.	-do-	0.000388	450000	2.0	140000	0.311
				2.5	175000	0.389
				3.0	200000	0.445
				3.5	220000	0.489

T A B L E- 5.A_8

Effect of various parameters on the ratio of onset of semi-fluidization to maximum semi- fluidization velocities.

(a) Influence of wall effect :-

Sl. No.	Operating parameter, D_c/d_p	G_{osf}/G_{msf}	Constant parameter
1.	10.42	0.5090	
2.	23.00	0.3490	ρ_s/ρ_f = 2.83
3.	46.15	0.2915	R = 2.00
4.	65.50	0.2480	
5.	93.00	0.2310	

(b) Effect of density ratio :-

Sl. No.	Operating parameter, ρ_s/ρ_f	G_{osf}/G_{msf}	Constant parameter
1.	2.83	0.349	
2.	3.72	0.393	D_c/d_p = 23.00
3.	4.45	0.375	R = 2.00
4.	5.25	0.400	
5.	2.83	0.248	
6.	3.72	0.338	D_c/D_p = 65.5
7.	4.45	0.333	R = 2.0
8.	5.25	0.311	

T A B L E-5.A_8 (contd.)

(c) effect of bed expansion ratio :-

Sl. No.	Operating parameter, R	G_{osf}/G_{msf}	Constant parameter
1.	2.0	0.349	
2.	2.5	0.399	$\rho_s/\rho_f = 2.83$
3.	3.0	0.475	$D_c/d_p = 23.0$
4.	3.5	0.512	
5.	2.0	0.248	
6.	2.5	0.308	$\rho_s/\rho_f = 2.83$
7.	3.0	0.347	$D_c/d_p = 65.5$
8.	3.5	0.387	

T A B L E- 5.A_9

Relation of velocity ratio (G_{osf}/G_{msf}) with system variables.

Sl. No.	D_c/d_p	ρ_s/ρ_f	R	Prod.	$\frac{G_{osf}}{G_{msf}}$
1	2	3	4	5	6
1.	10.42	2.83	2.0	0.901	0.5090
2.	23.00	2.83	2.0	0.674	0.3490
3.	46.15	2.83	2.0	0.519	0.2915
4.	65.50	2.83	2.0	0.459	0.2480
5.	93.00	2.83	2.0	0.402	0.2310
6.	23.00	3.72	2.0	0.729	0.3930
7.	23.00	4.45	2.0	0.767	0.3750
8.	23.00	5.25	2.0	0.804	0.4000
9.	23.00	2.83	2.5	0.780	0.3990
10.	23.00	2.83	3.0	0.878	0.4750
11.	23.00	2.83	3.5	0.975	0.5120
12.	65.50	3.72	2.0	0.496	0.3380
13.	65.50	4.45	2.0	0.523	0.3330
14.	65.50	5.25	2.0	0.548	0.3110
15.	65.50	2.83	2.5	0.532	0.3080
16.	65.50	2.83	3.0	0.599	0.3470
17.	65.50	2.83	3.5	0.665	0.3870
18.	10.42	2.83	2.5	1.042	0.5970
19.	10.42	2.83	3.0	1.174	0.6380
20.	10.42	2.83	3.5	1.303	0.6690

Contd...

TABLE- 5.A_9 (Contd.)

1	2	3	4	5	6
21.	46.15	2.83	2.5	0.599	0.3600
22.			3.0	0.675	0.4060
23.			3.5	0.749	0.4600
24.	93.00	2.83	2.5	0.465	0.2990
25.			3.0	0.523	0.3420
26.			3.5	0.581	0.3890
27.	23.00	3.72	2.5	0.844	0.4650
28.			3.0	0.950	0.5290
29.			3.5	1.055	0.5790
30.	65.50	3.72	2.5	0.574	0.4060
31.			3.0	0.646	0.4530
32.			3.5	0.718	0.4850
33.	23.00	4.45	2.5	0.887	0.4370
34.			3.0	0.999	0.5000
35.			3.5	1.109	0.5500
36.	65.50	4.45	2.5	0.605	0.3980
37.			3.0	0.681	0.4490
38.			3.5	0.756	0.5000
39.	23.00	5.25	2.5	0.931	0.4510
40.			3.0	1.049	0.5130
41.			3.5	1.164	0.5640
42.	65.50	5.25	2.5	0.634	0.3890
43.			3.0	0.714	0.4450
44.			3.5	0.793	0.4890

TABLE- 5.B7

Ratio of minimum to maximum semi-fluidization velocity (Experimental)

Sl. No.	System	d_p m	G_{msf} Kg./Hr.M^2	R	G_{osf} Kg./Hr.M^2	$\frac{G_{osf}}{G_{msf}}$
1	2	3	4	5	6	7
1.	Dolomite- air	0.002435	43000	2.0	7500	0.1742
				2.5	8000	0.1860
				3.0	8500	0.1975
				3.5	9000	0.2095
2.	Dolomite- air	0.001104	28000	2.0	3950	0.1411
				2.5	4300	0.1535
				3.0	4725	0.1688
				3.5	5275	0.1882
3.	Dolomite- air	0.000550	17000	2.0	2200	0.1295
				2.5	2600	0.1530
				3.0	3000	0.1765
				3.5	3300	0.1941
4.	Dolomite- air	0.000388	14000	2.0	1550	0.1108
				2.5	1650	0.1180
				3.0	2200	0.1570
				3.5	2500	0.1785
5.	Chromite- air	0.001104	32000	2.0	5000	0.1562
				2.5	5800	0.1812
				3.0	6300	0.1970
				3.5	6800	0.2125

T A B L E-5.B_7 (Contd.)

1	2	3	4	5	6	7
6.	Baryte- air	0.001104	36000	2.0	5500	0.1528
				2.5	5900	0.1640
				3.0	6500	0.1806
				3.5	7000	0.1945
7.	Iron ore-air	0.001104	40000	2.0	6400	0.1600
				2.5	6900	0.1725
				3.0	7500	0.1875
				3.5	8000	0.2000

TABLE- 5.B8

Effect of various parameters on the ratio of onset of semifluidization to maximum semi-fluidization velocities.

(a) Influence of wall effect :-

Sl. No.	Operating parameter, D_c/d_p	G_{osf}/G_{msf}	Constant parameters
1.	18.10	0.1742	ρ_s / ρ_f = 1210
2.	39.80	0.1411	R = 2.0
3.	80.00	0.1295	
4.	113.30	0.1108	

(b) Effect of density ratio :-

Sl. No.	Operating parameter, ρ_s / ρ_f	G_{osf}/G_{msf}	Constant parameters.
1.	1210.0	0.1411	D_c / d_p = 39.80
2.	1590.0	0.1562	R = 2.0
3.	1900.0	0.1528	
4.	2244.0	0.1600	

(c) Effect of bed expansion ratio :-

Sl. No.	Operating parameter, R	G_{osf}/G_{msf}	Constant pparameters.
1.	2.0	0.1411	ρ_s / ρ_f =1210
2.	2.5	0.1535	D_c / d_p =39.80
3.	3.0	0.1688	
4.	3.5	0.1882	

T A B L E- 5.B_9

Relation of velocity ratio (G_{osf}/G_{msf}) with system variables.

Sl. No.	$\frac{D_c}{d_p}$	$\frac{\rho_s}{\rho_f}$	R	Prod.	$\frac{G_{osf}}{G_{msf}}$
1	2	3	4	5	6
1.	18.10	1210.0	2.0	3.694	0.1742
2.	39.80	1210.0	2.0	2.929	0.1411
3.	80.00	1210.0	2.0	2.388	0.1295
4.	113.30	1210.0	2.0	2.156	0.1108
5.	39.80	1590.0	2.0	3.129	0.1562
6.	39.80	1900.0	2.0	3.270	0.1528
7.	39.80	2244.0	2.0	3.410	0.1600
8.	39.80	1210.0	2.5	3.323	0.1535
9.	39.80	1210.0	3.0	3.674	0.1688
10.	39.80	1210.0	3.5	4.010	0.1882

Contd...2

TABLE- 5.B_9 (Contd.)

1	2	3	4	5	6
11.	18.10	1210.0	2.5	4.190	0.1860
12.			3.0	4.633	0.1975
13.			3.5	5.056	0.2095
14.	80.00	1210.0	2.5	2.709	0.1530
15.			3.0	2.995	0.1760
16.			3.5	3.268	0.1940
17.	113.30	1210.0	2.5	2.446	0.1180
18.			3.0	2.704	0.1570
19.			3.5	2.951	0.1785
20.	39.80	1590.0	2.5	3.551	0.1812
21.			3.0	3.926	0.1970
22.			3.5	4.284	0.2125
23.	39.80	1900.0	2.5	3.711	0.1640
24.			3.0	4.104	0.1806
25.			3.5	4.478	0.1945
26.	39.80	2244.0	2.5	3.870	0.1725
27.			3.0	4.280	0.1875
28.			3.5	4.670	0.2000

TABLE- 5.A10

Comparison of the onset of semi-fluidization velocities.

Sl. No.	System	d_p m	G_{msf} Kg./Hr.M^2 (by equation)	R	G_{osf}, $\frac{Kg.}{Hr.\ M^2}$ From expt.	From correlation.	Percentage deviation of calculated values from the experimental values.
1	2	3	4	5	6	7	8
1.	Dolomite-water	0.002435	924070	2.0	415000	425257	+2.47
				2.5	486250	462682	-4.85
				3.0	520000	496041	-4.61
				3.5	545000	526073	-3.47
2.	-do-	0.001104	551780	2.0	216250	216684	+0.20
				2.5	247500	235720	-4.76
				3.0	295000	252715	-14.33
				3.5	317500	268000	-15.59
3.	-do-	0.000550	350870	2.0	113750	119822	+5.34
				2.5	140500	130383	-7.20
				3.0	158500	139752	-11.83
				3.5	179500	148243	-17.41
4.	-do-	0.000388	279310	2.0	77000	88904	+15.46
				2.5	95500	96753	+1.31
				3.0	107500	103708	-3.53
				3.5	120000	109992	-8.34
5.	-do-	0.000273	222330	2.0	52000	66054	+27.03
				2.5	67250	71879	+6.88
				3.0	77000	77060	+0.08
				3.5	87500	81729	-6.60

TABLE-5.A_{10} (Contd.)

1	2	3	4	5	6	7	8
6.	Chromite-water	0.001104	685300	2.0	275000	281864	+2.50
				2.5	325000	306672	-5.64
				3.0	370000	328738	-11.15
				3.5	405000	348681	-13.91
7.	-do-	0.000388	346890	2.0	108000	115723	+7.15
				2.5	130000	125886	-3.16
				3.0	145000	134975	-6.91
				3.5	155000	143127	-7.66
8.	Baryte-water	0.001104	781690	2.0	300000	331358	+10.45
				2.5	350000	360515	+3.00
				3.0	400000	386468	-3.38
				3.5	440000	409918	-6.84
9.	-do-	0.000388	395680	2.0	130000	135995	+4.61
				2.5	155000	147984	-4.53
				3.0	175000	158628	-9.36
				3.5	195000	168243	-13.72
10.	Iron ore-water	0.001104	879840	2.0	390000	383698	+1.62
				2.5	440000	417484	-5.12
				3.0	500000	447575	-10.49
				3.5	550000	474674	-13.70
11.	-do-	0.000388	445370	2.0	140000	157483	+12.49
				2.5	175000	171334	-2.09
				3.0	200000	183671	-8.16
				3.5	220000	194805	-11.45

TABLE- 5.B_{10}

Comparison of the onset of semifluidization velocities.

Sl. No.	System	d_p m	G_{msf}, $\frac{Kg.}{Hr.M^2}$ (by equation)	R	G_{osf}, $\frac{Kg.}{Hr.M^2}$ From experiment.	From correlation	Percentage deviation of calculated values from the experimental values.
1	2	3	4	5	6	7	8
1.	Dolomite-air	0.002435	46050	2.0	7500	7976	+ 6.35
				2.5	8000	8680	+ 8.50
				3.0	8500	9302	+ 9.44
				3.5	9000	9869	+ 9.66
2.	-do-	0.001104	27700	2.0	3950	4100	+ 3.80
				2.5	4300	4460	+ 3.72
				3.0	4725	4781	+ 1.19
				3.5	5275	5072	- 3.85
3.	-do-	0.000550	17570	2.0	2200	2258	+ 2.64
				2.5	2600	2456	- 5.54
				3.0	3000	2632	-12.27
				3.5	3300	2792	-15.39
4.	-do-	0.000388	13980	2.0	1550	1679	+ 8.32
				2.5	1650	1827	+10.73
				3.0	2200	1959	-10.95
				3.5	2500	2077	-16.92

TABLE- 5.B_{10} (contd.)

1	2	3	4	5	6	7	8
5.	Chromite-air	0.001104	31800	2.0	5000	4926	- 1.48
				2.5	5800	5358	- 7.62
				3.0	6300	5743	- 8.84
				3.5	6800	6093	-10.40
6.	Baryte-air	0.001104	35050	2.0	5500	5594	+ 1.71
				2.5	5900	6085	+ 3.14
				3.0	6500	6523	+ 0.35
				3.5	7000	6919	- 1.16
7.	Iron ore-air.	0.001104	38750	2.0	6400	6359	- 0.64
				2.5	6900	6921	+ 0.30
				3.0	7500	7417	- 1.11
				3.5	8000	7866	- 1.68

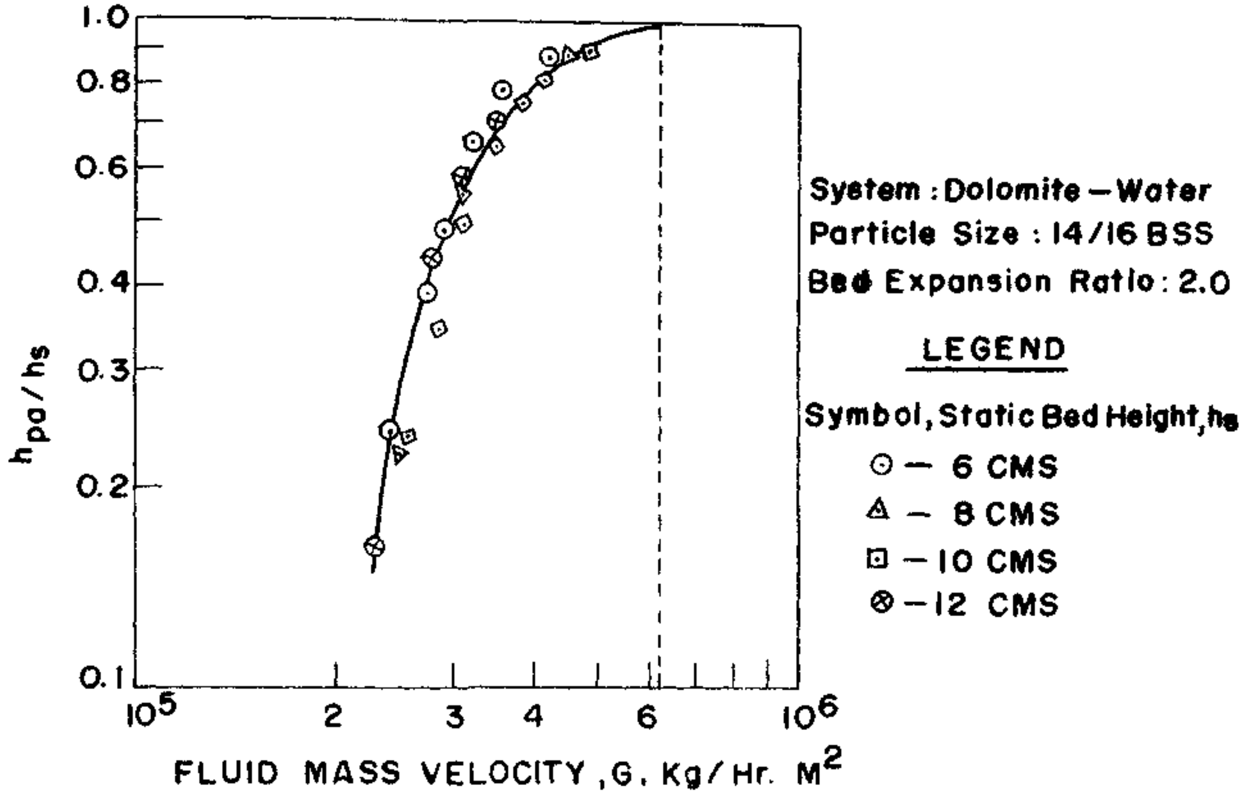


FIG. 5. A1 EFFECT OF INITIAL STATIC BED HEIGHT (h_s) ON MAX.M SEMI-FLUIDIZATION VELOCITY.

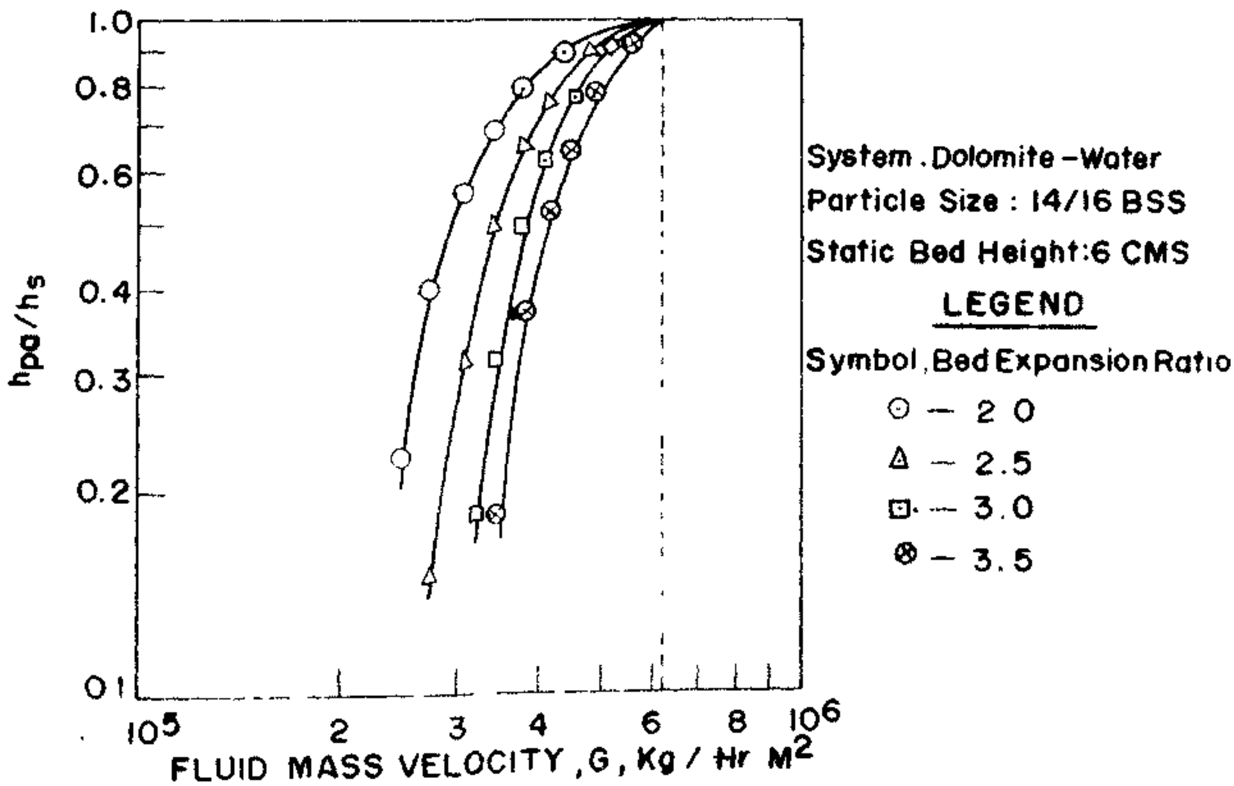


FIG. 5. A2 EFFECT OF BED EXPANSION RATIO (R) ON MAX.M SEMI-FLUIDIZATION VELOCITY.

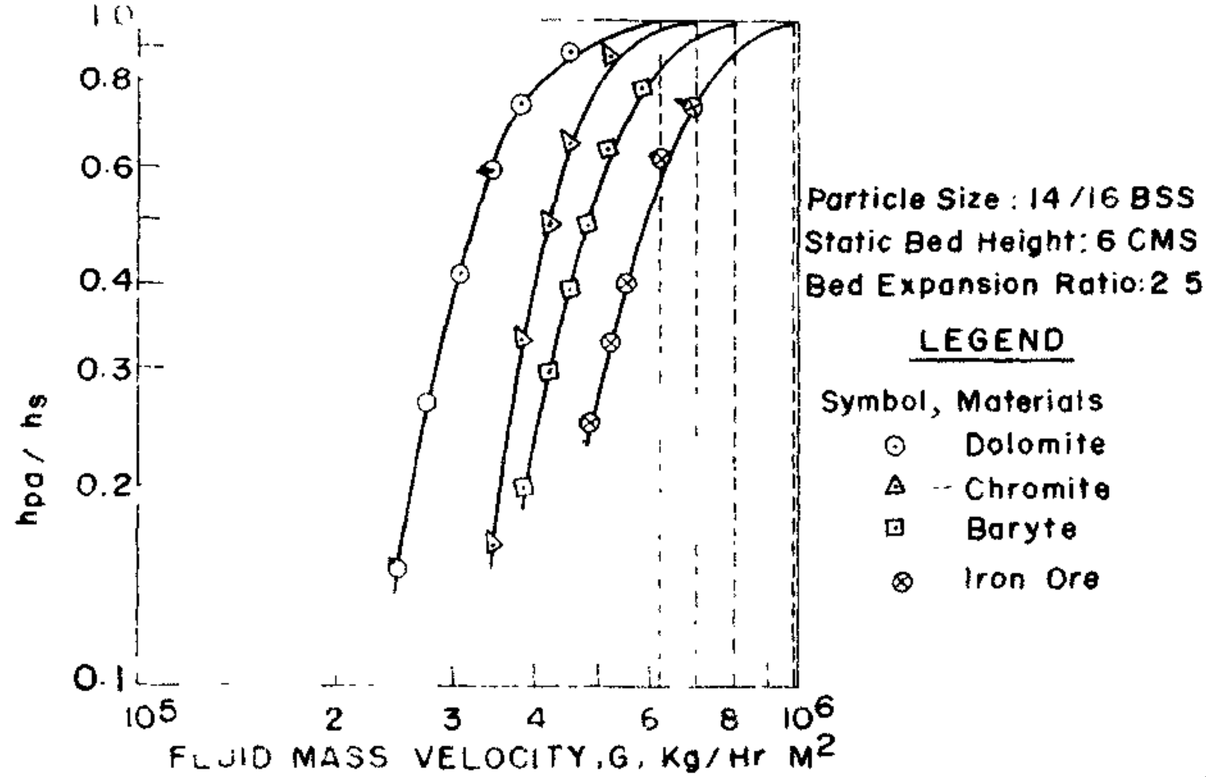


FIG 5 A_3 EFFECT OF DENSITY OF MATERIAL ON MAX.[M] SEMI-FLUIDIZATION VELOCITY

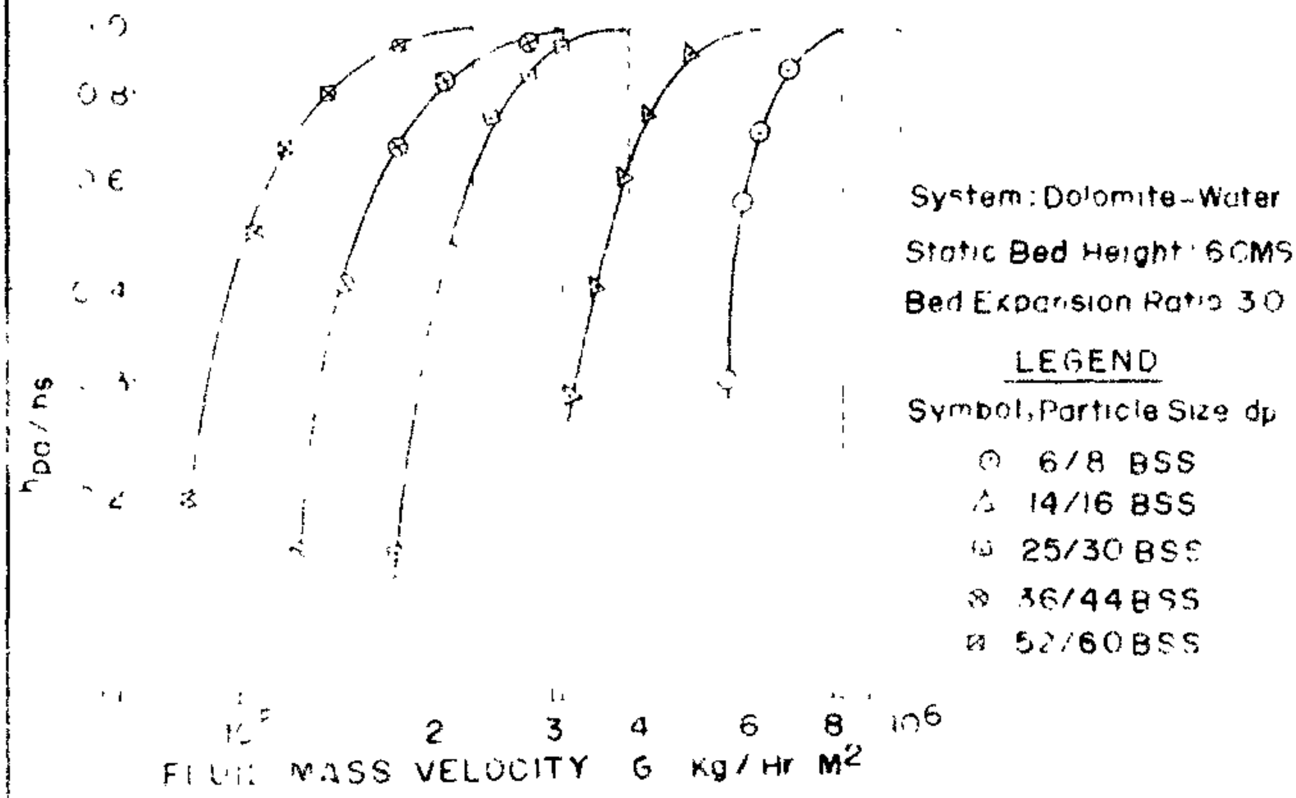


FIG 5 A_4 EFFECT OF PARTICLE SIZE (dp) ON MAX[M] SEMI-FLUIDIZATION VELOCITY.

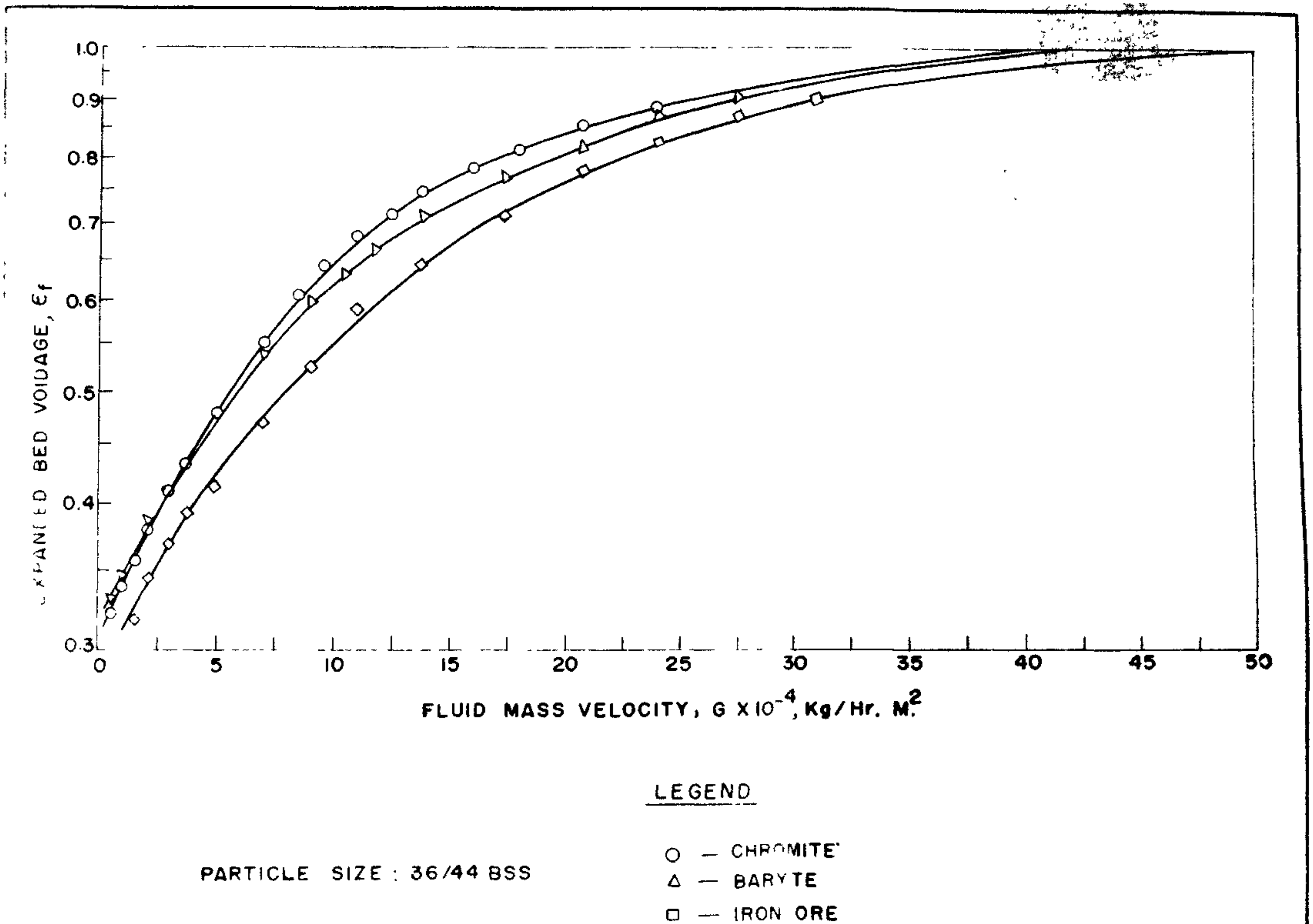


FIG. 5. A_5 PREDICTION OF MAXIMUM SEMI-FLUIDIZATION VELOCITY FROM BED EXPANSION DATA.

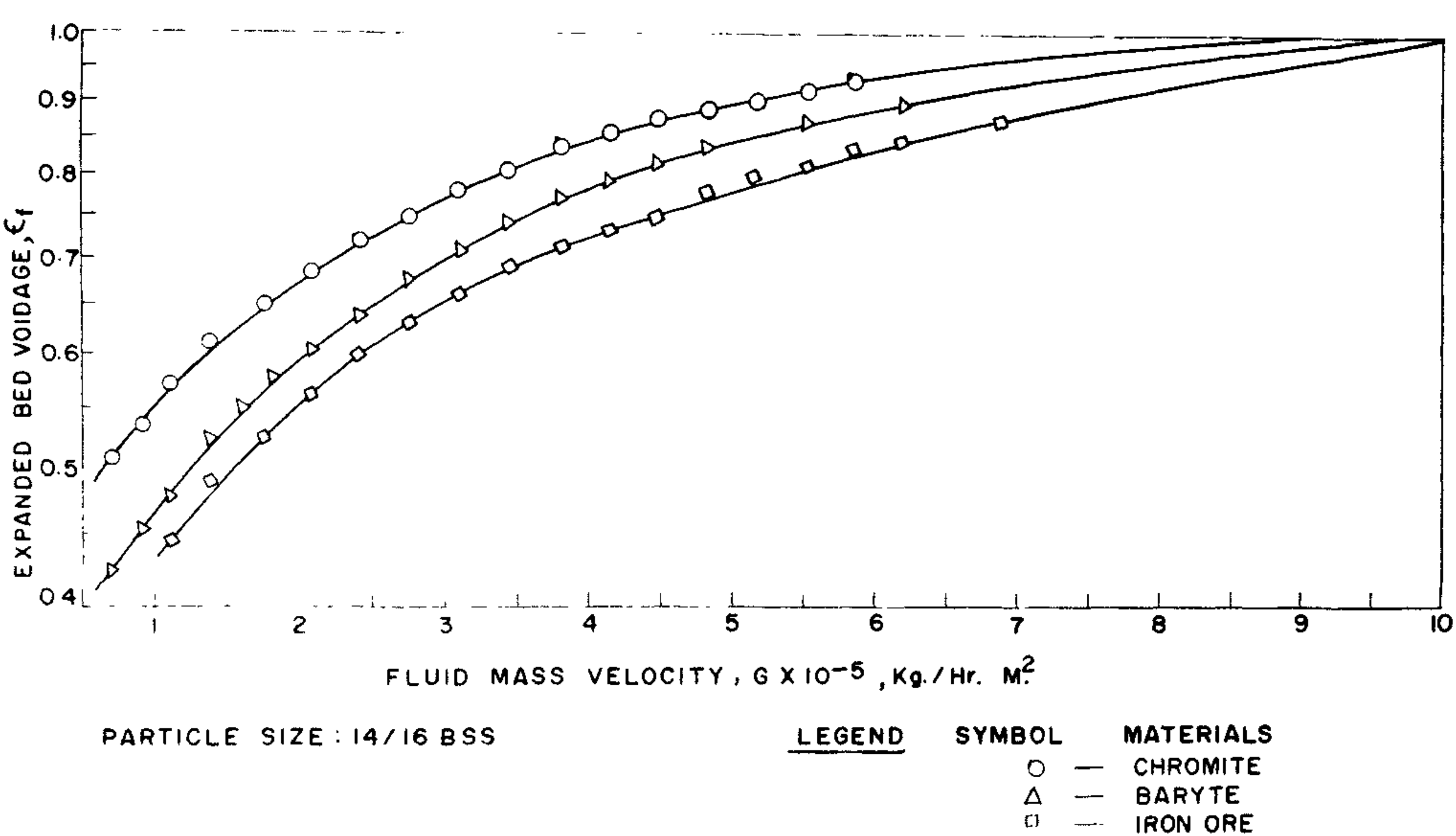


FIG 5. A_6 PREDICTION OF MAXIMUM SEMI-FLUIDIZATION VELOCITY FROM BED EXPANSION DATA.

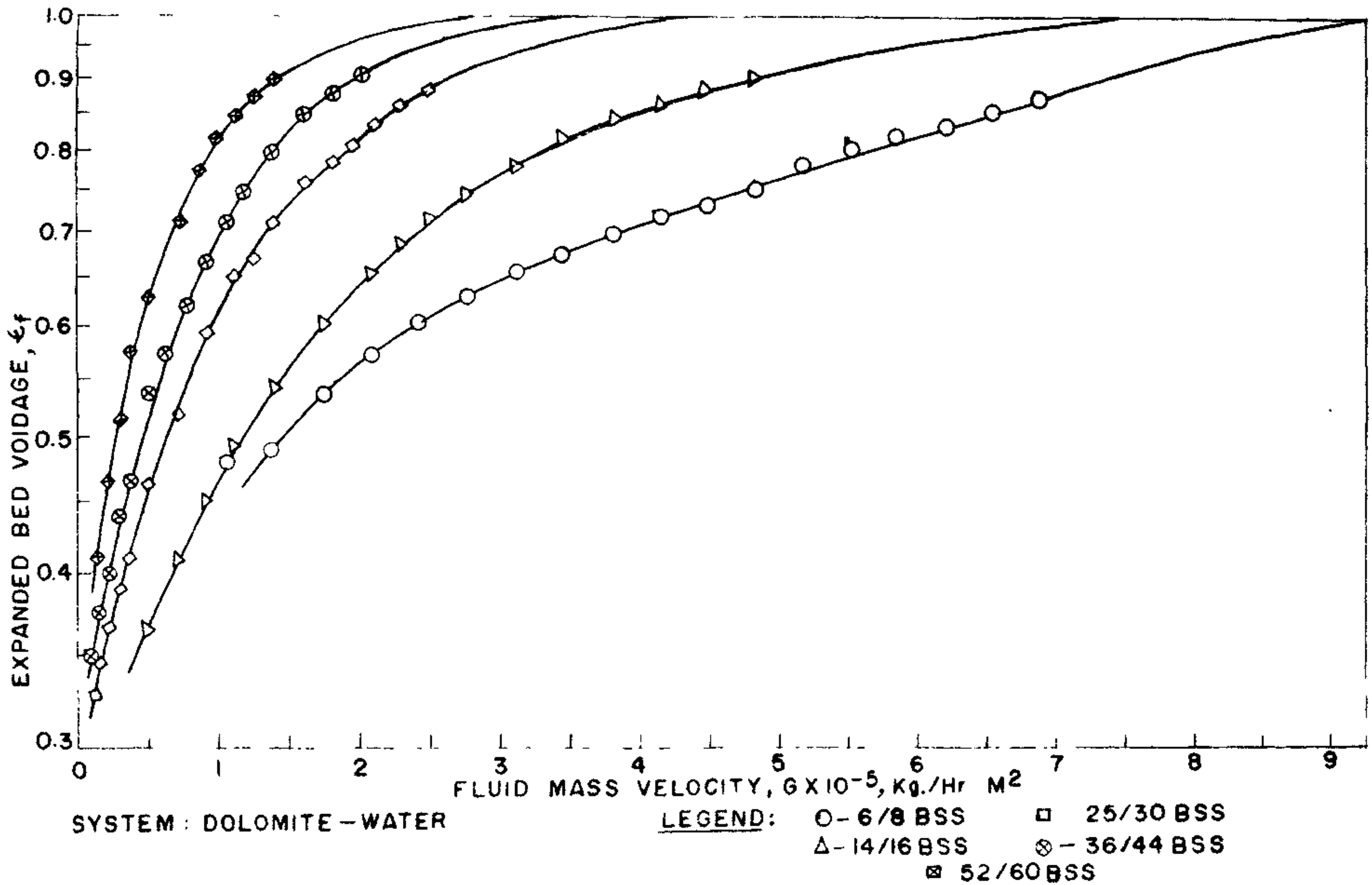


FIG. 5. A$_7$ PREDICTION OF MAXIMUM SEMI – FLUIDIZATION VELOCITY FROM BED EXPANSION DATA.

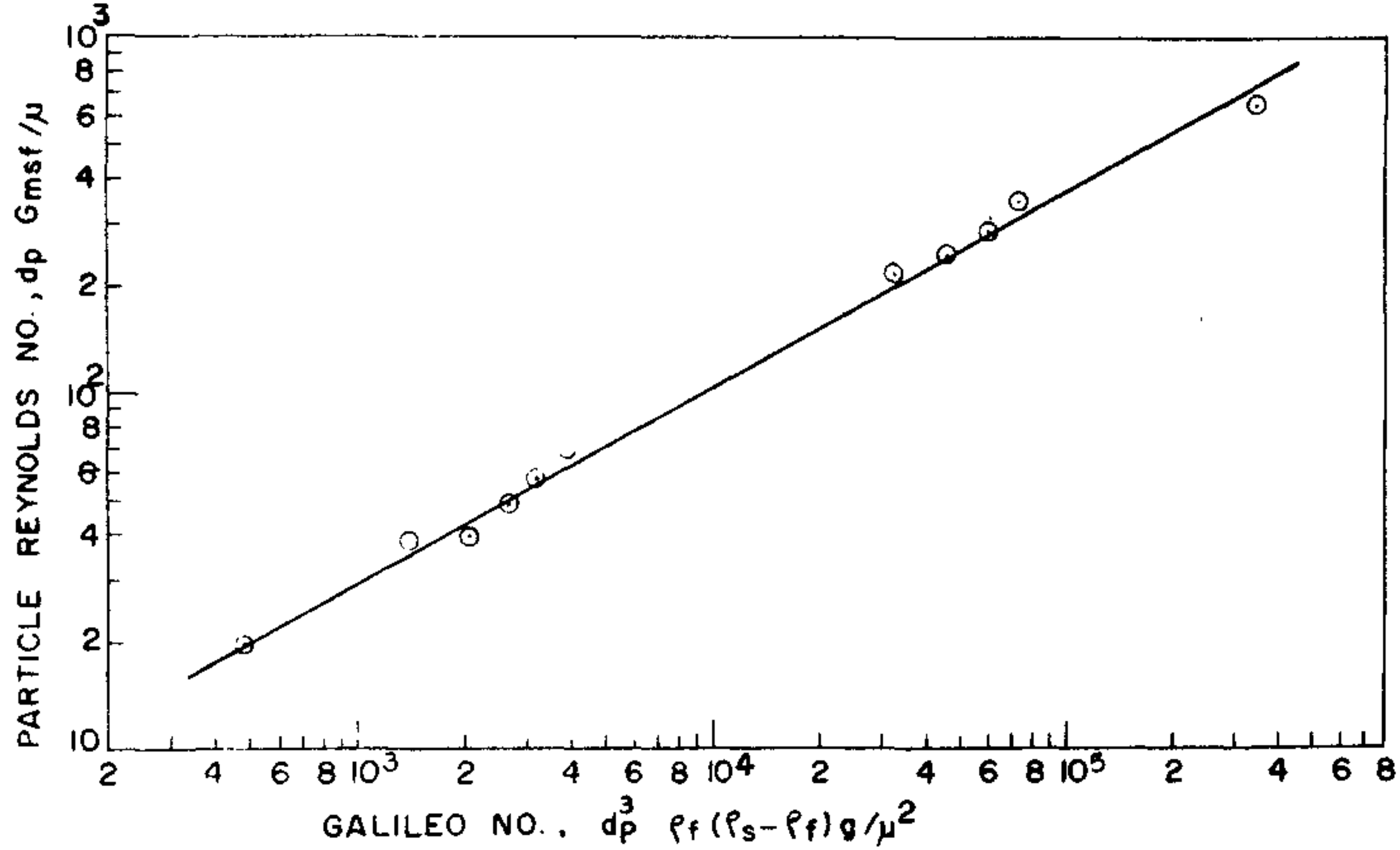


FIG 5.A_8 RELATION OF MAXIMUM SEMI-FLUIDIZATION VELOCITY WITH SYSTEM VARIABLES

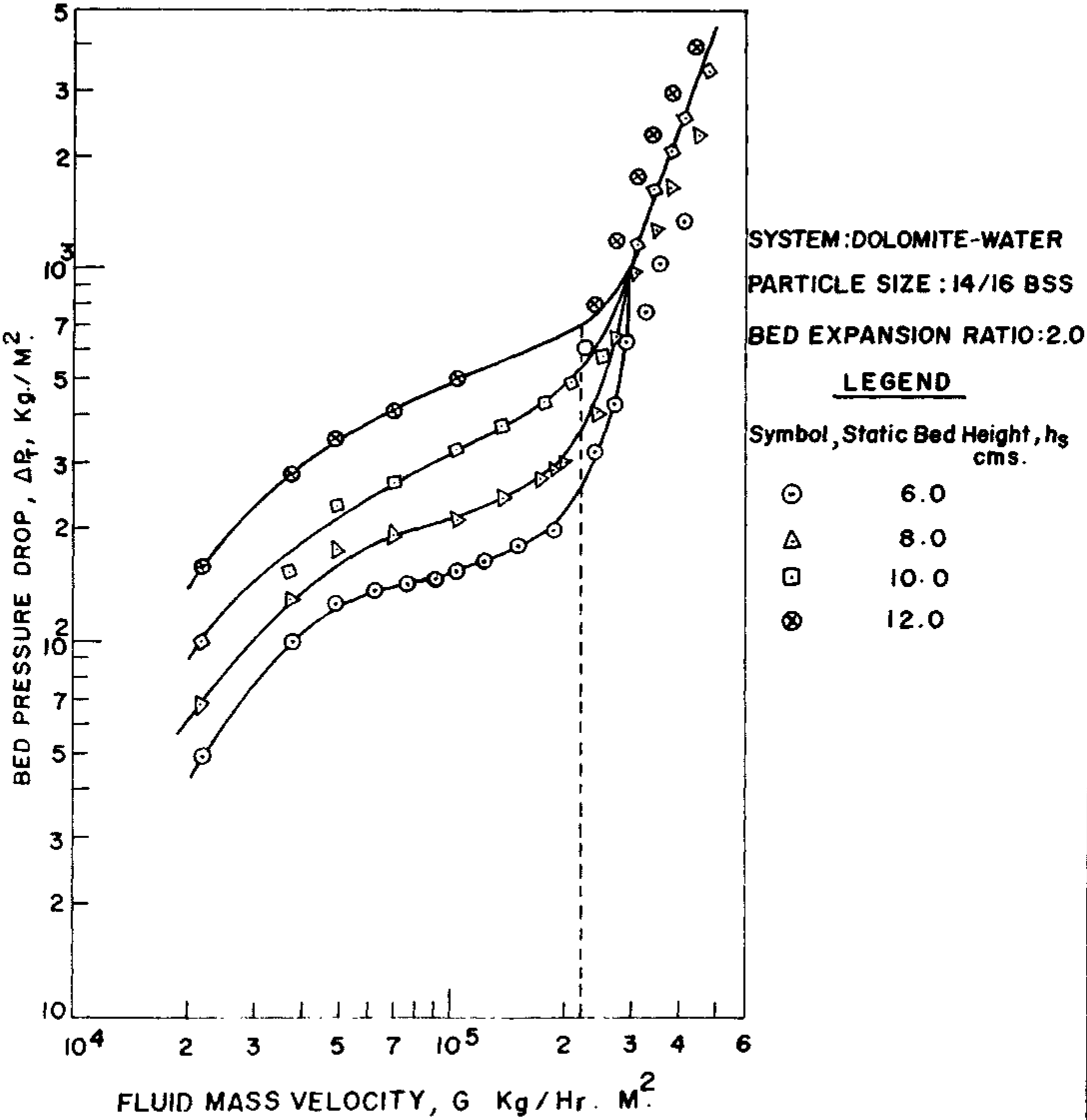
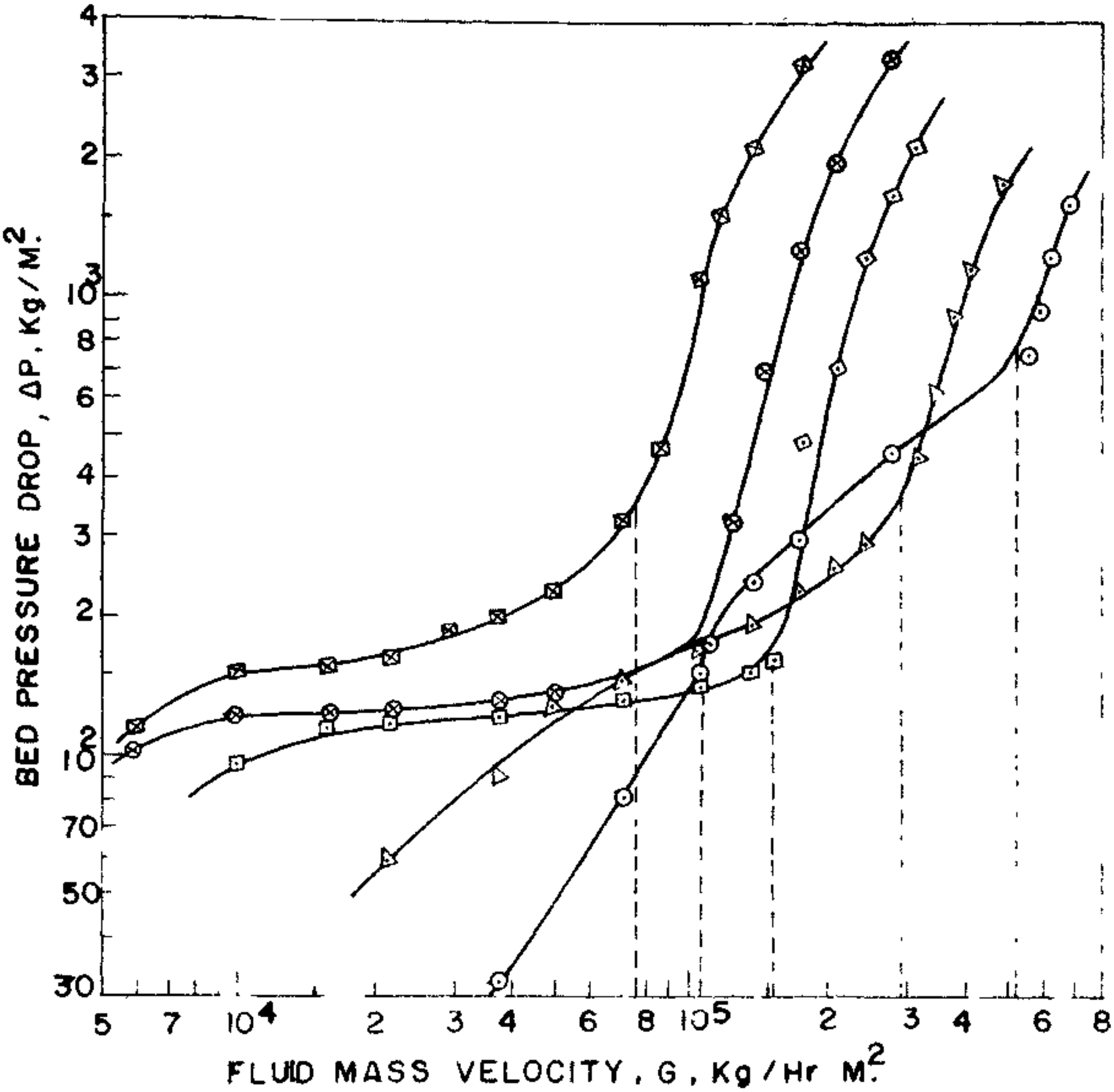


FIG. 5. A_9 EFFECT OF INITIAL STATIC BED HEIGHT ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY.

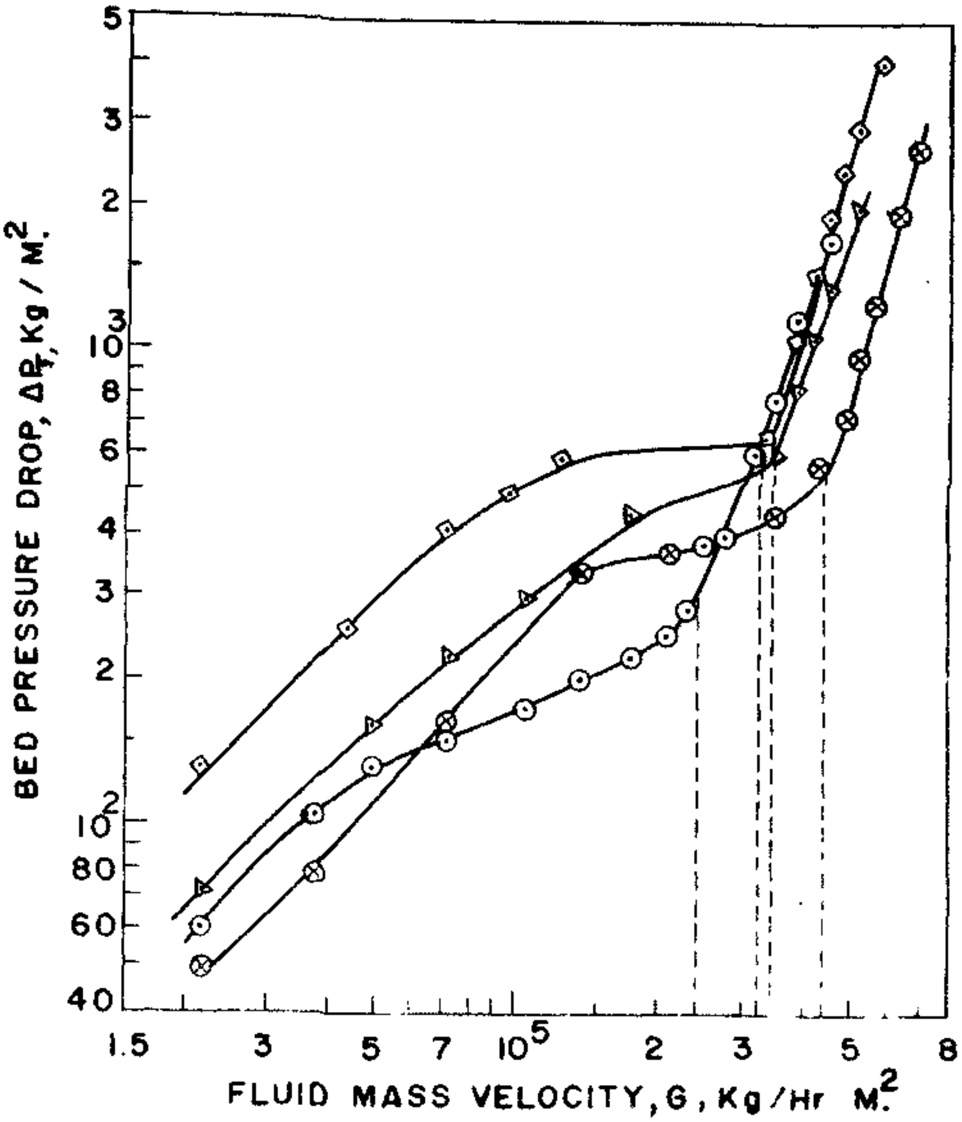


SYSTEM : DOLOMITE - WATER
STATIC BED HEIGHT : 6 CMS.
BED EXPANSION RATIO: 3.0

LEGEND

SYMBOL	PARTICLE SIZE, dp
⊙	— 6/8 BSS
△	— 14/16 BSS
⊡	— 25/30 BSS
⊗	— 36/44 BSS
⊠	— 52/60 BSS

FIG 5 A_{10} EFFECT OF PARTICLE SIZE ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY



PARTICLE SIZE : 14/16 BSS

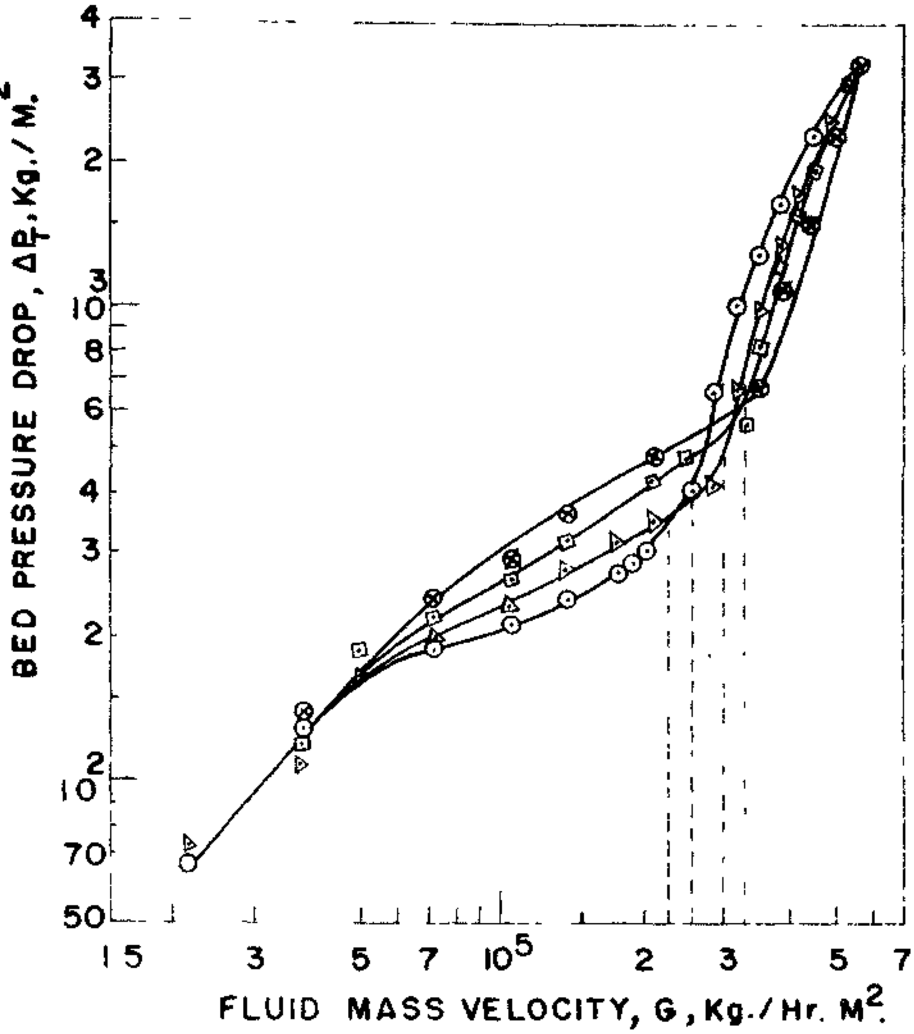
STATIC BED HEIGHT : 6 CMS.

BED EXPANSION RATIO : 2.5

LEGEND

SYMBOL	MATERIALS
⊙	DOLOMITE
⊡	BARYTE
⊗	IRON ORE
△	CHROMITE

FIG. 5 A_{II} EFFECT OF DENSITY OF MATERIALS ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY



SYSTEM . DOLOMITE – WATER

PARTICLE SIZE : 14/16 BSS

STATIC BED HEIGHT : 10 CMS.

LEGEND

SYMBOL	BED EXPANSION RATIO (R)
○	2.0
△	2.5
⊡	3.0
⊗	3.5

FIG 5 A_{12} EFFECT OF BED EXPANSION RATIO ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY.

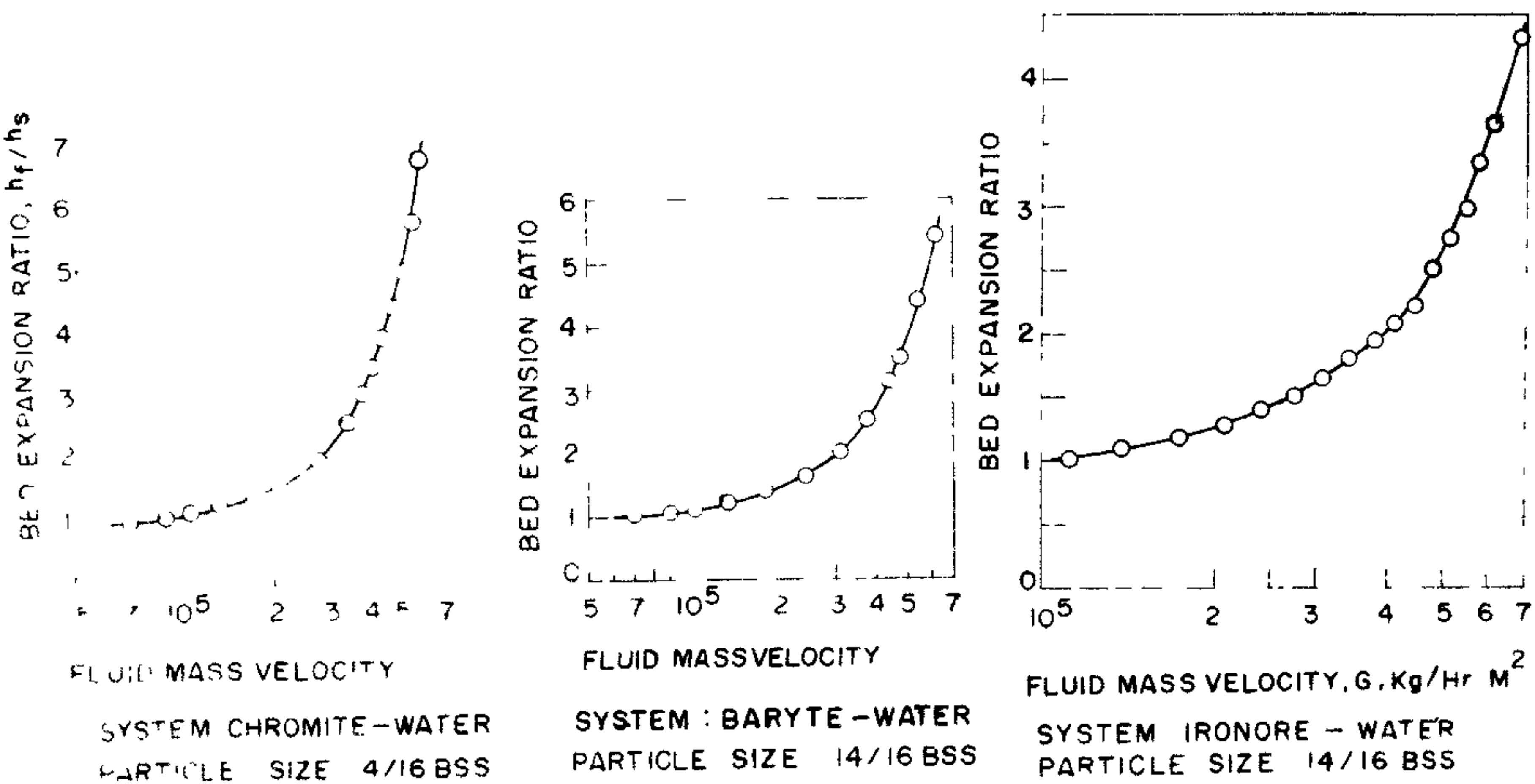
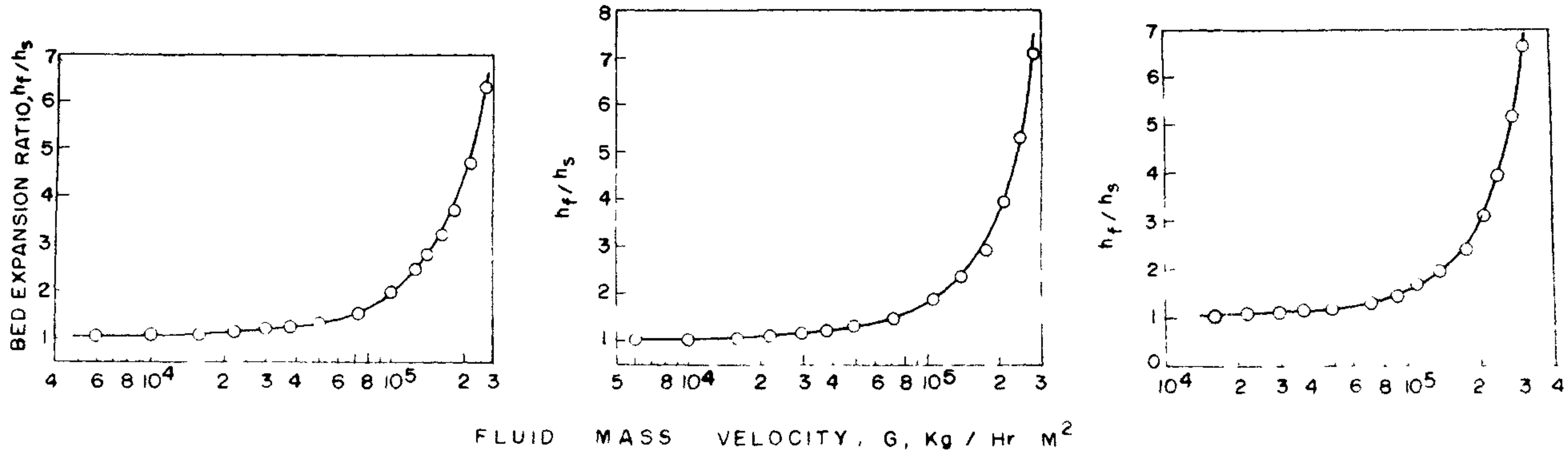


FIG 5 A_{13} PREDICTION OF MINIMUM SEMI-FLUIDIZATION VELOCITY FROM BED EXPANSION DATA



SYSTEM CHROMITE – WATER
PARTICLE SIZE 36/44 BSS

SYSTEM BARYTE – WATER
PARTICLE SIZE 36/44 BSS

SYSTEM IRONORE – WATER
PARTICLE SIZE 36/44 BSS

FIG 5 A_{14} PREDICTION OF MINIMUM SEMI–FLUIDIZATION VELOCITY FROM BED EXPANSION DATA.

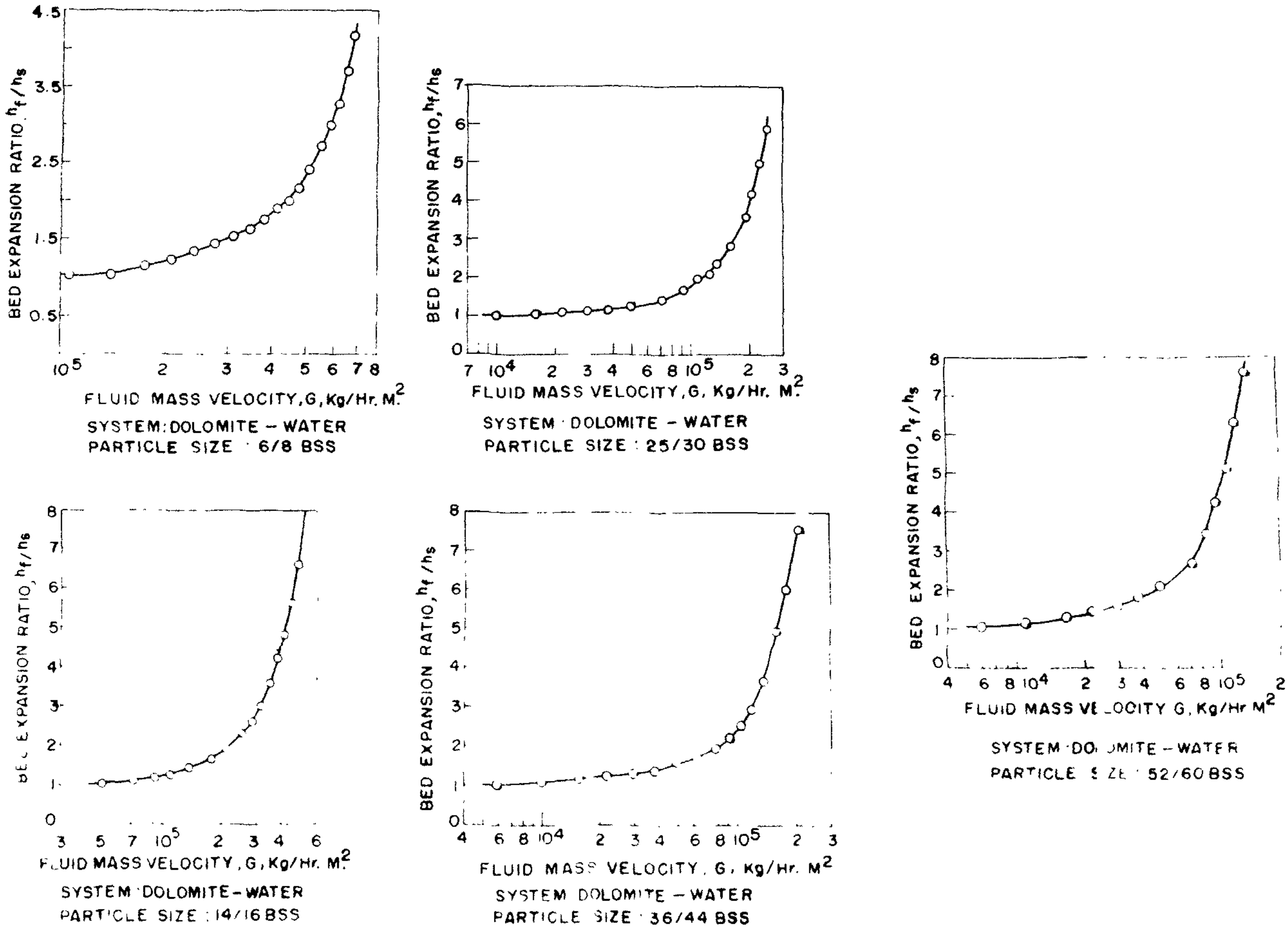


FIG. 5 A15 PREDICTION OF MINIMUM SEMI-FLUIDIZATION VELOCITY FROM BED EXPANSION DATA .

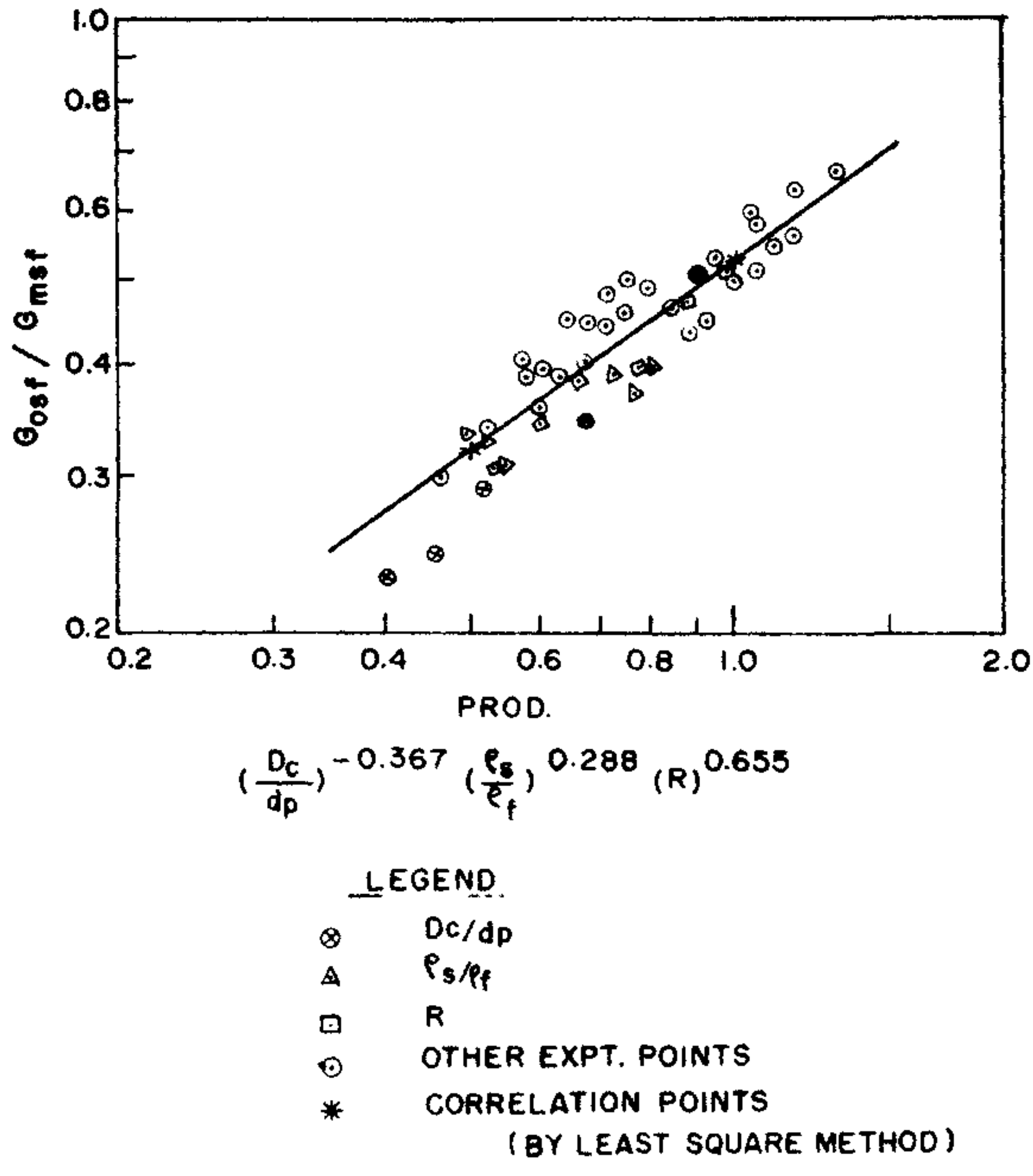


FIG. 5. A_{16} RELATION OF Gosf/Gmsf WITH SYSTEM VARIABLES.

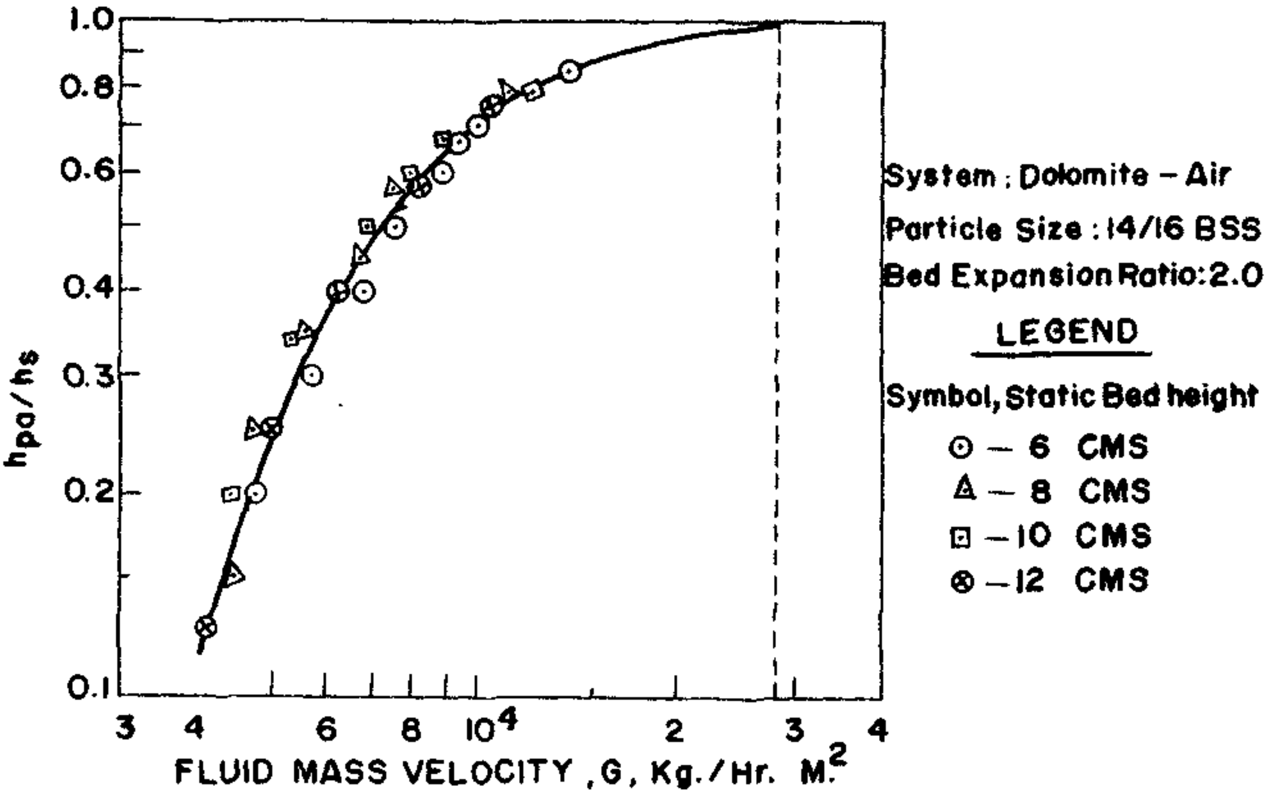


FIG. 5 B_1 EFFECT OF INITIAL STATIC BED HEIGHT ON MAX.[M] SEMI-FLUIDIZATION VELOCITY.

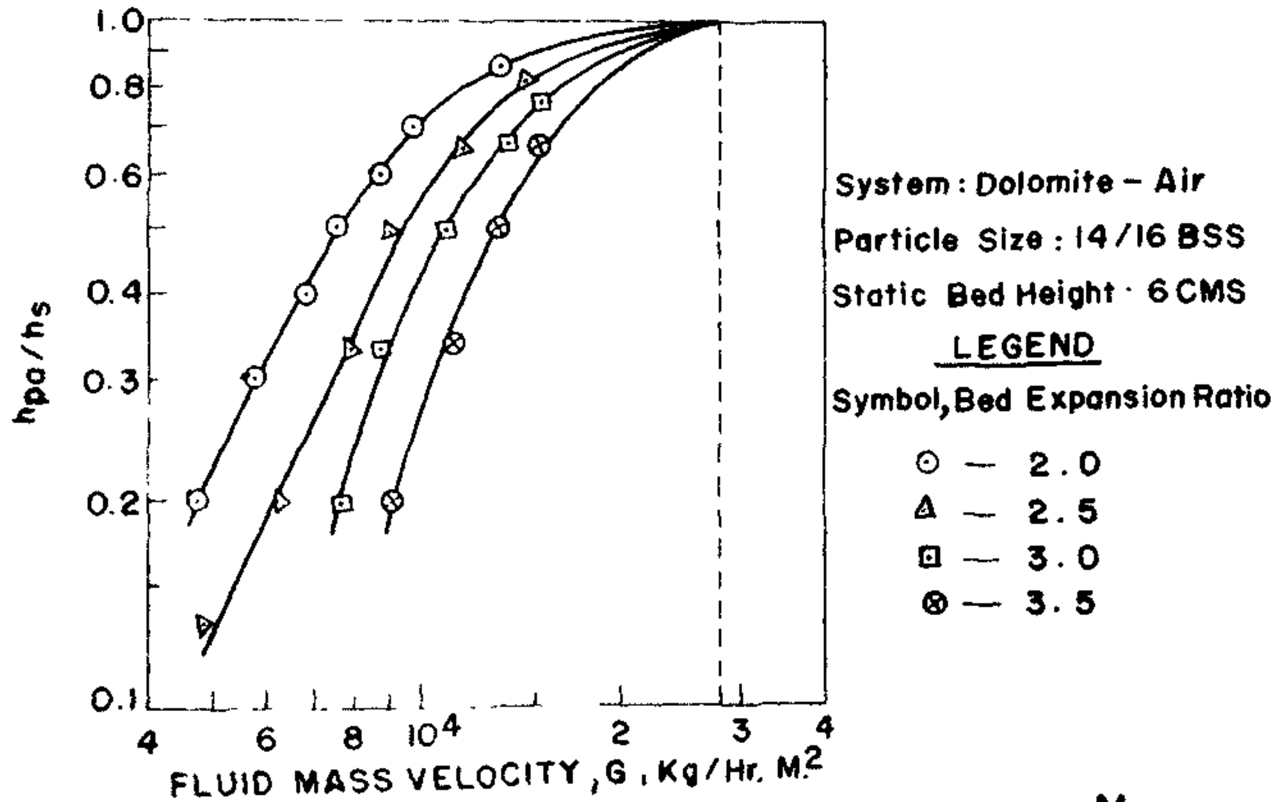


FIG. 5. B_2 EFFECT OF EXPANSION RATIO ON MAX.[M] SEMI-FLUIDIZATION VELOCITY

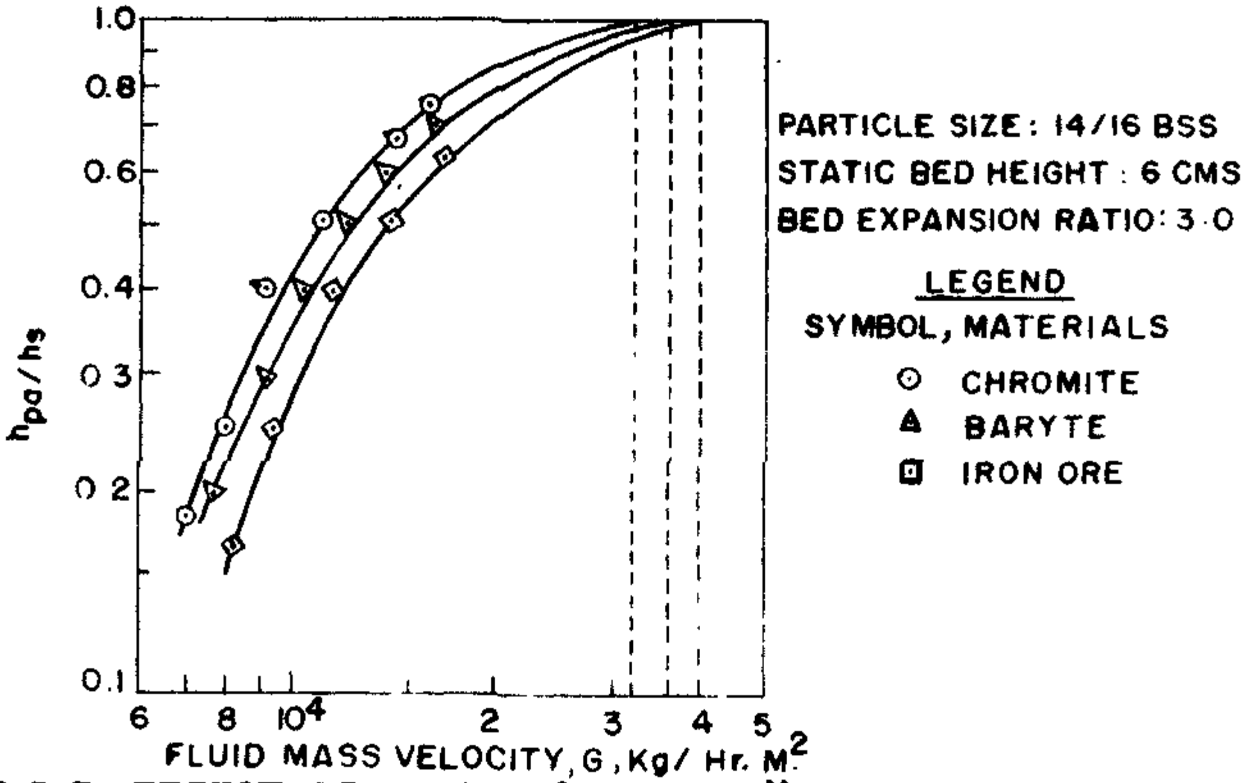
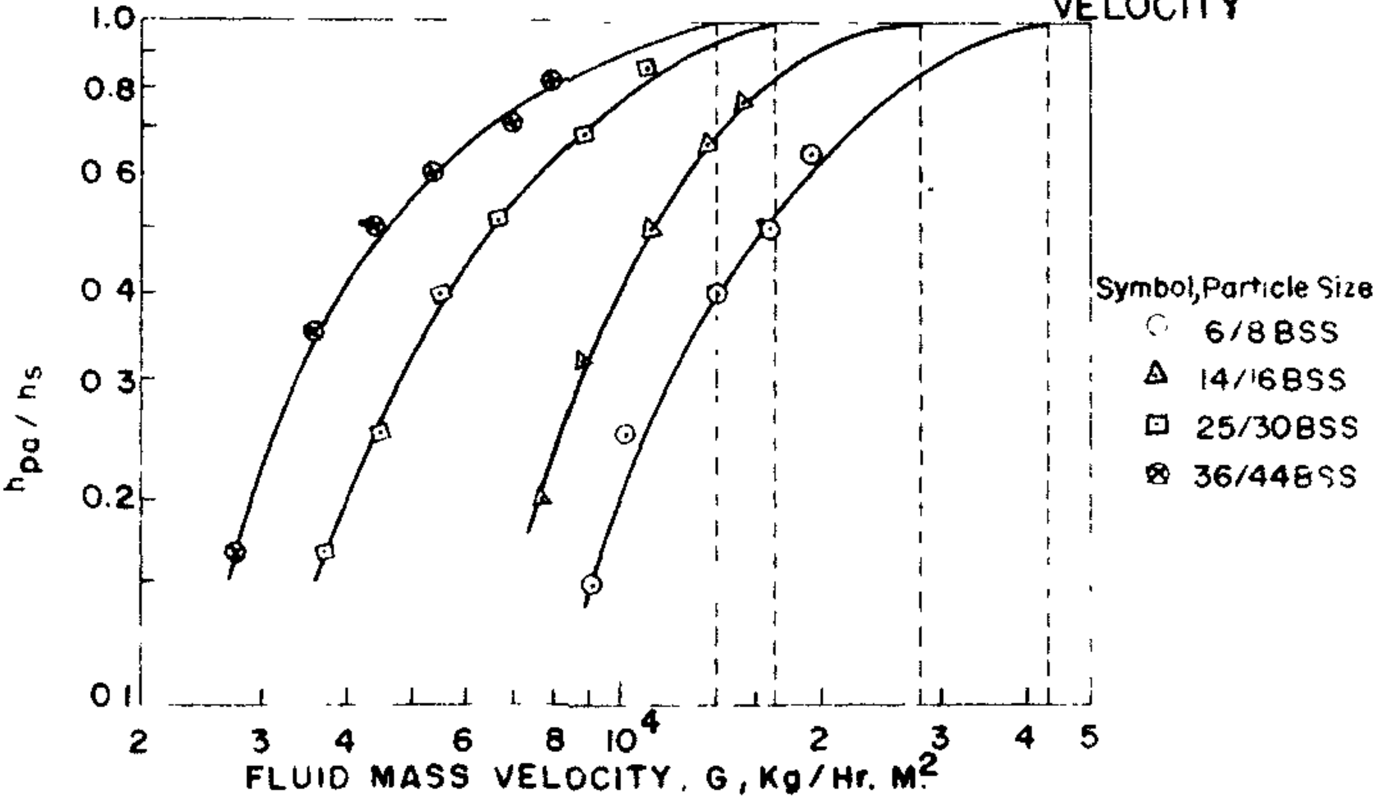


FIG 5.B3 EFFECT OF DENSITY (ρ_s) ON MAX.M SEMI-FLUIDIZATION VELOCITY



SYSTEM . DOLOMITE - AIR , STATIC BED HEIGHT. 6 CMS

BED EXPANSION RATIO : 3·0

FIG. 5. B4 EFFECT OF PARTICLE SIZE ON MAX.M SEMI-FLUIDIZATION VELOCITY.

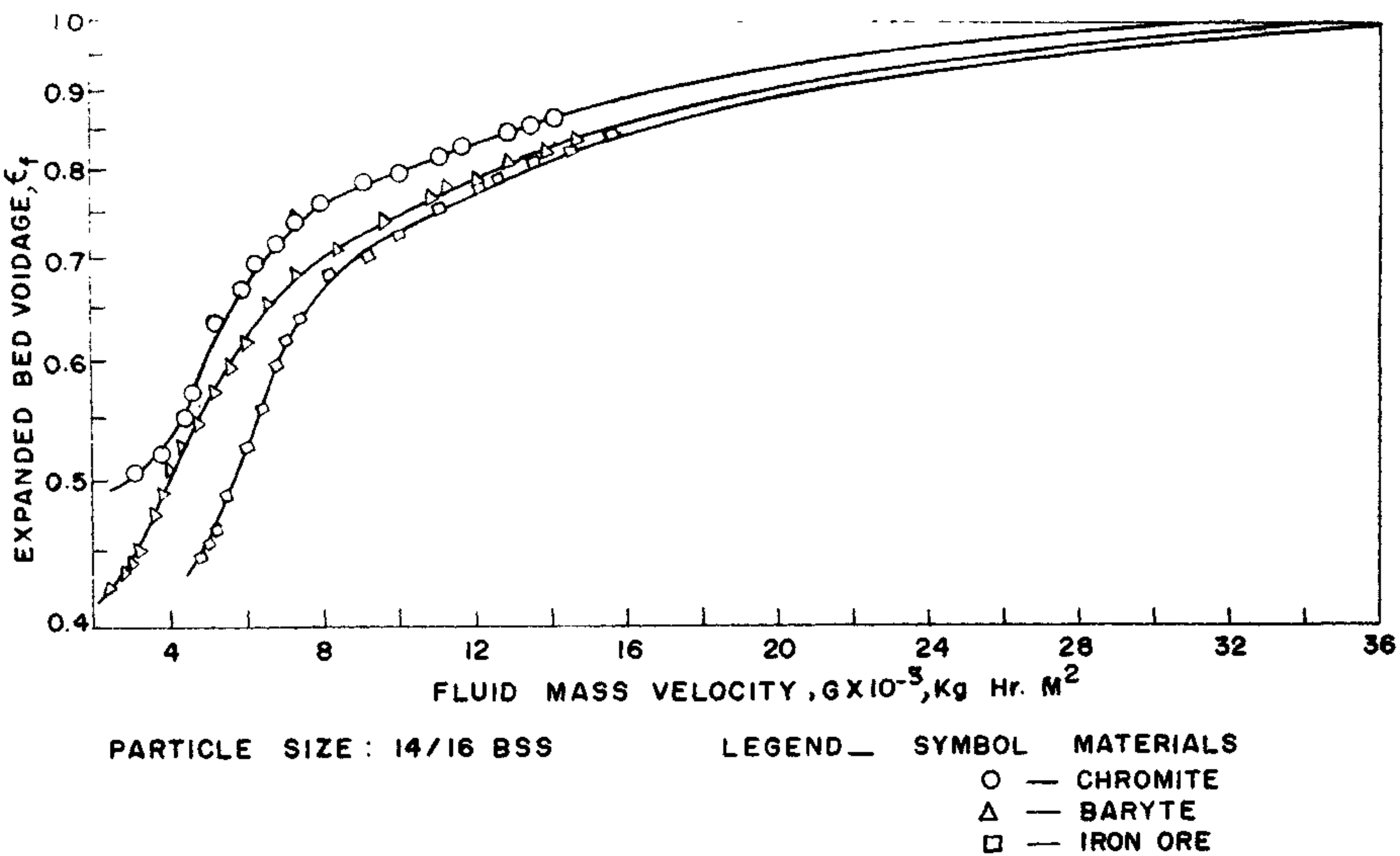


FIG. 5. B_5 PREDICTION OF MAXIMUM SEMI-FLUIDIZATION VELOCITIES FROM EXPANSION DATA.

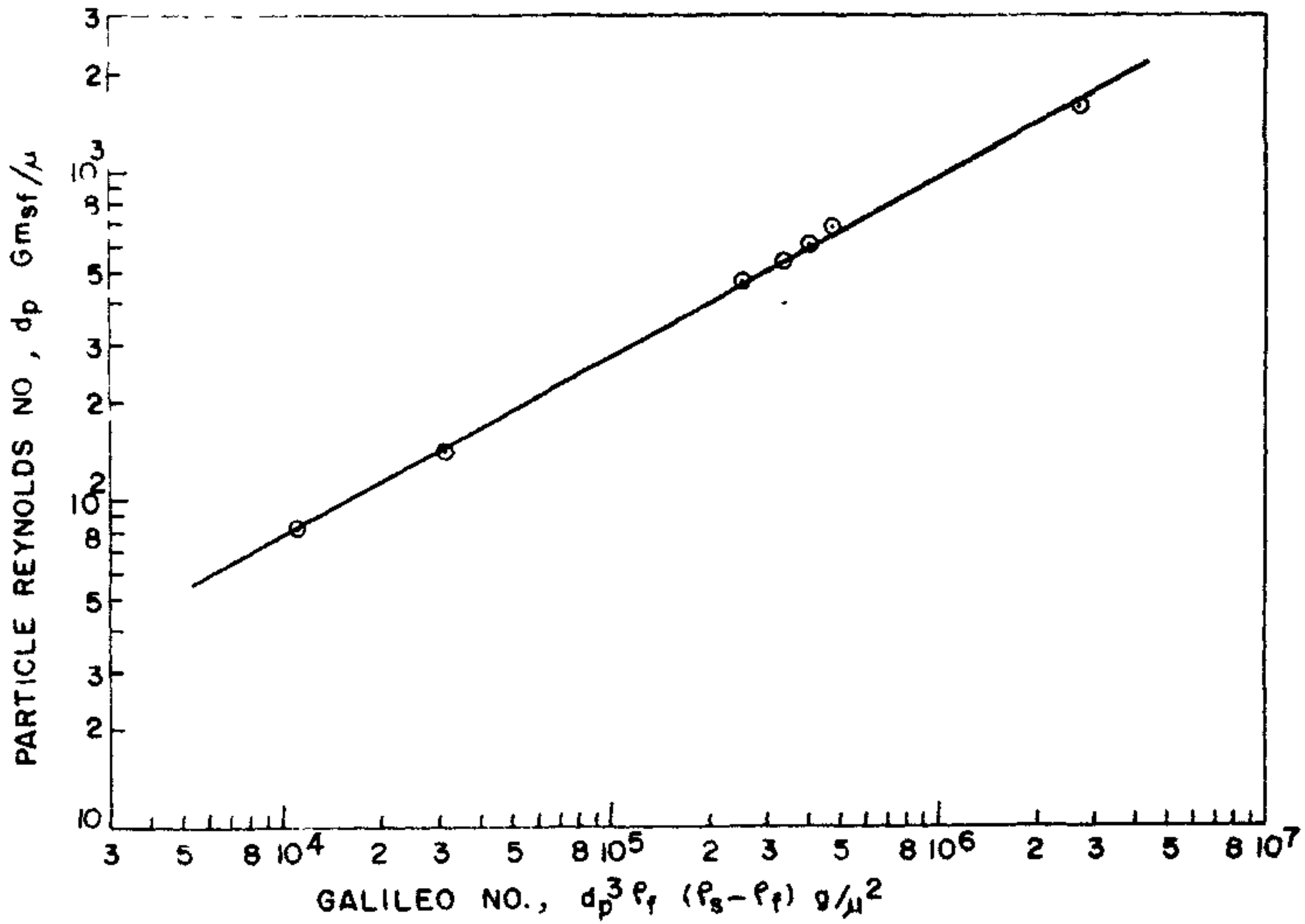
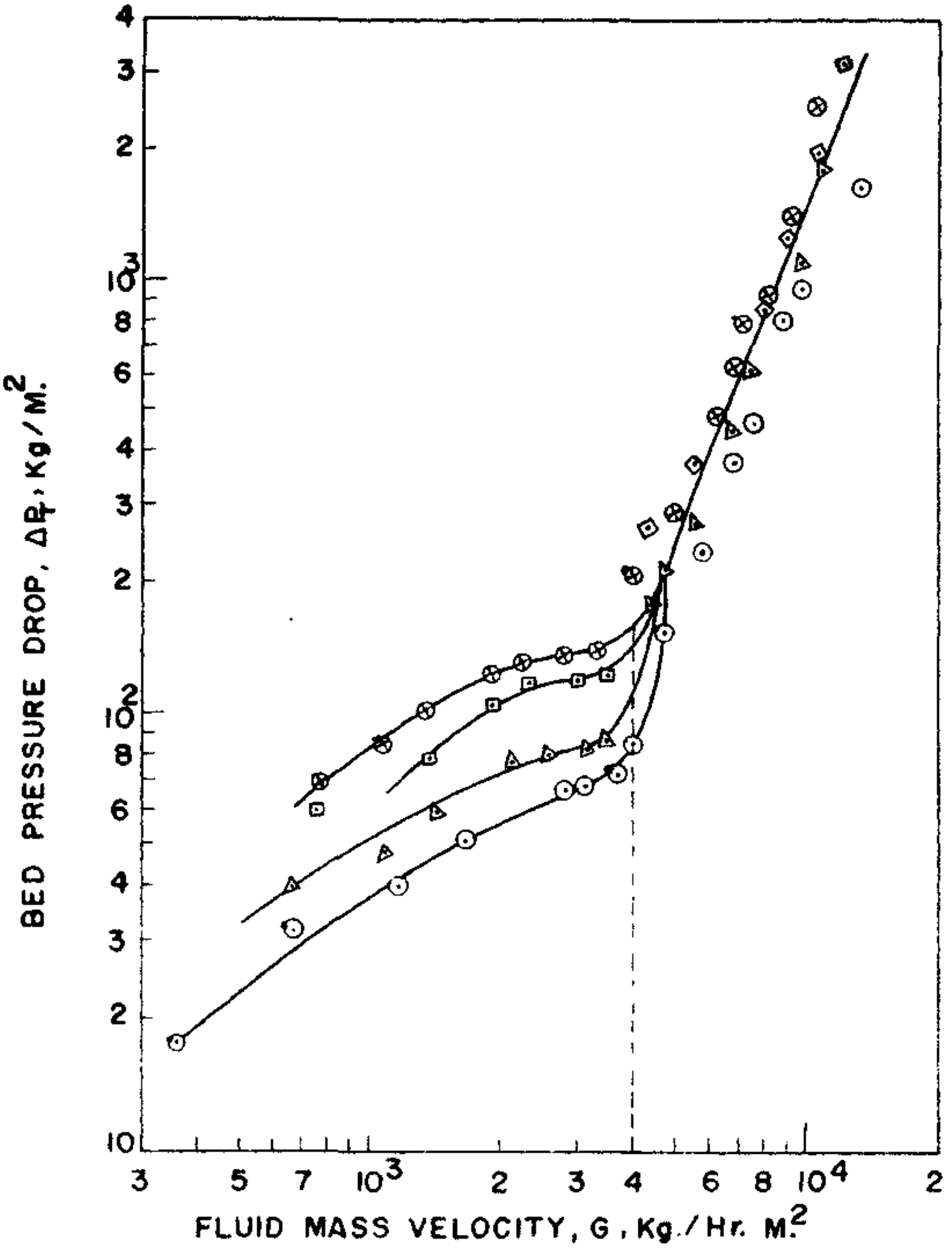


FIG. 5. B$_7$ RELATION OF MAXIMUM SEMI-FLUIDIZATION VELOCITY WITH SYSTEM VARIABLES.



SYSTEM: DOLOMITE-AIR

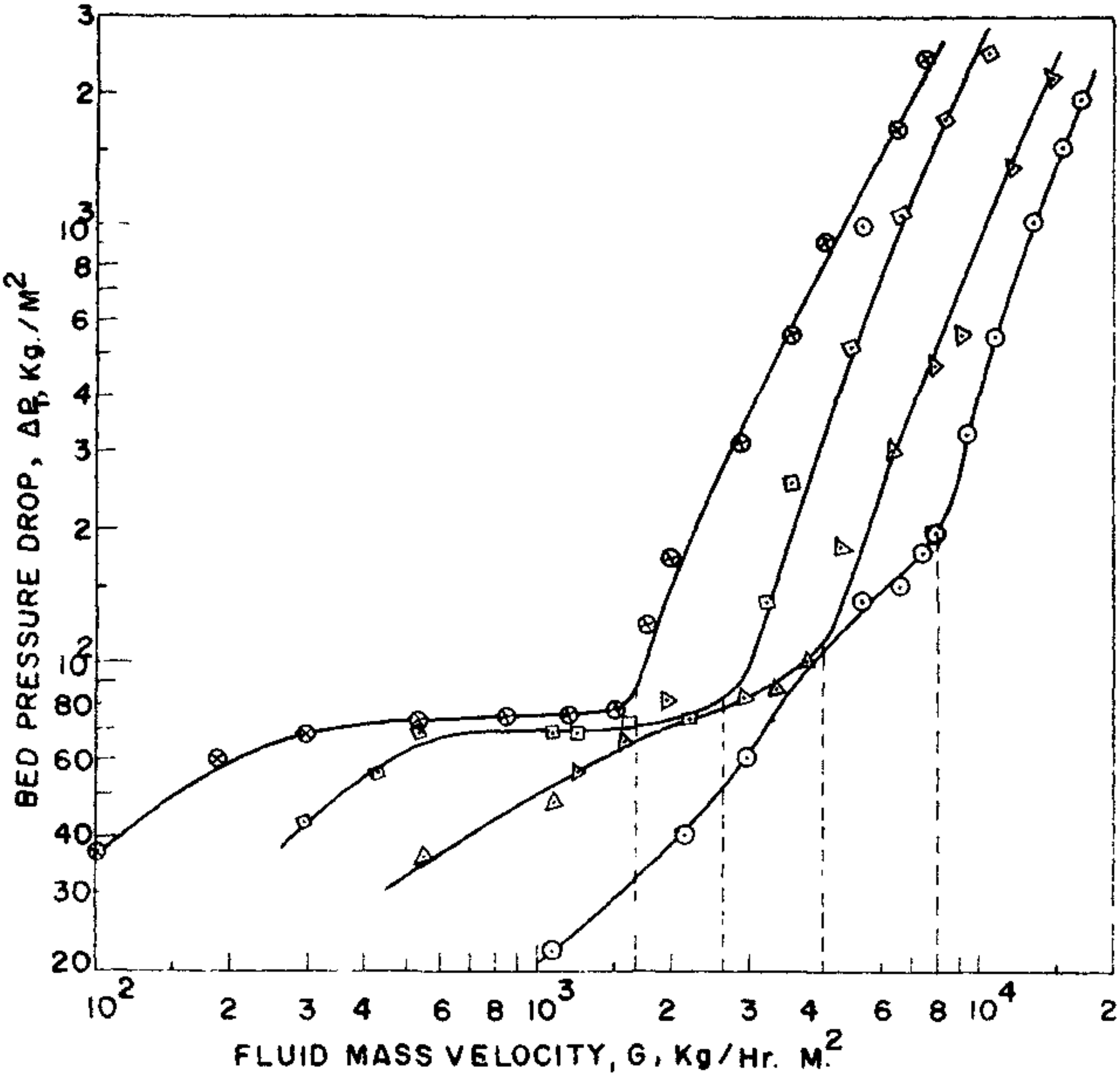
PARTICLE SIZE: 14/16 BSS

BED EXPANSION RATIO: 2.0

LEGEND

SYMBOL	STATIC BED HEIGHT
○	6 CMS
△	8 CMS
⊡	10 CMS
⊗	12 CMS

FIG. 5. B8 EFFECT OF INITIAL STATIC BED HEIGHT ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY.



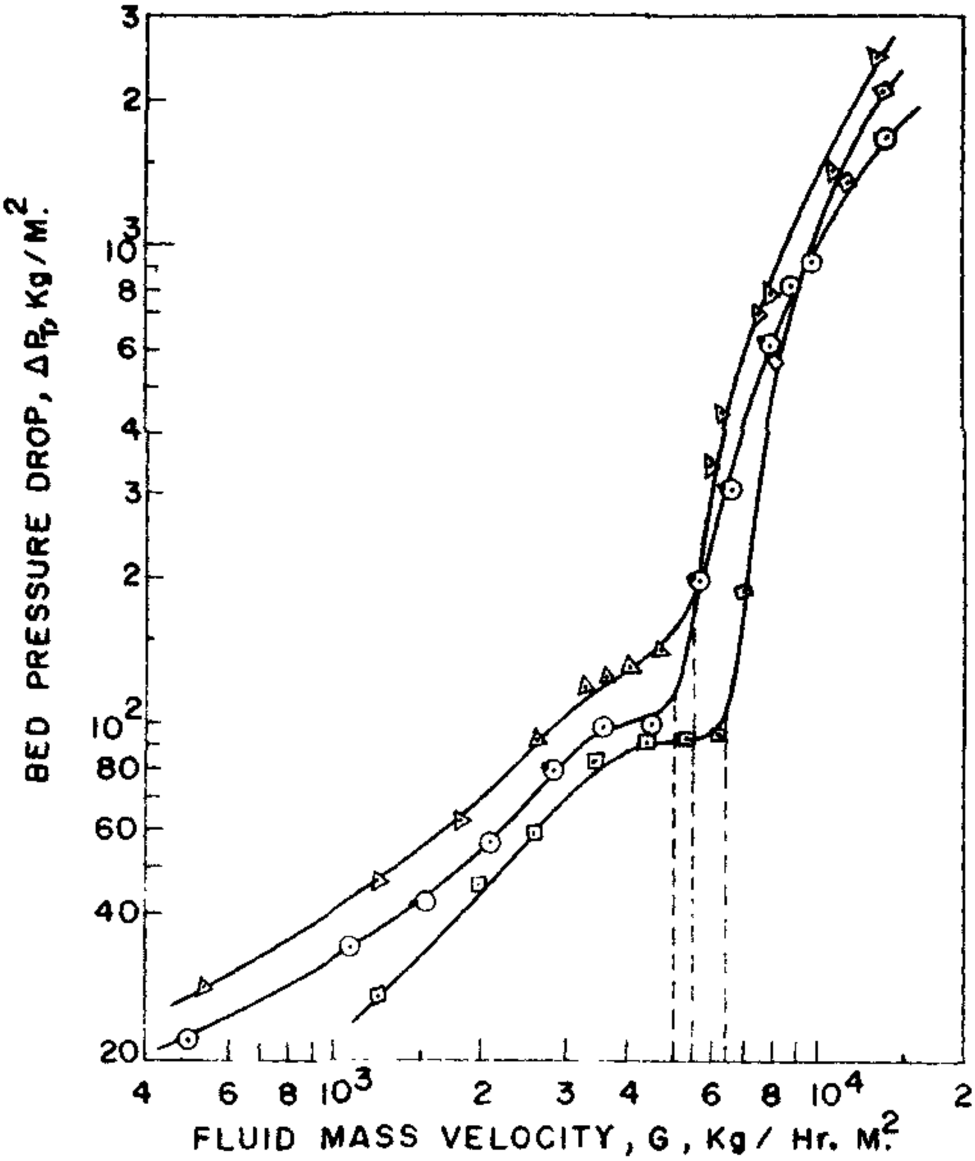
SYSTEM . DOLOMITE – AIR
STATIC BED HEIGHT : 6 CMS
BED EXPANSION RATIO : 2.5

LEGEND

SYMBOL, PARTICLE SIZE, dp, BSS

○	6/8
△	14/16
⊡	25/30
⊗	36/44

FIG. 5. B9 EFFECT OF PARTICLE SIZE ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY



PARTICLE SIZE : 14 / 16 BSS

STATIC BED HEIGHT : 6 CMS.

BED EXPANSION RATIO: 2.0

LEGEND

⊙ CHROMITE

△ BARYTE

⊡ IRON ORE

FIG 5 B_{10} EFFECT OF DENSITY OF MATERIALS ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY.

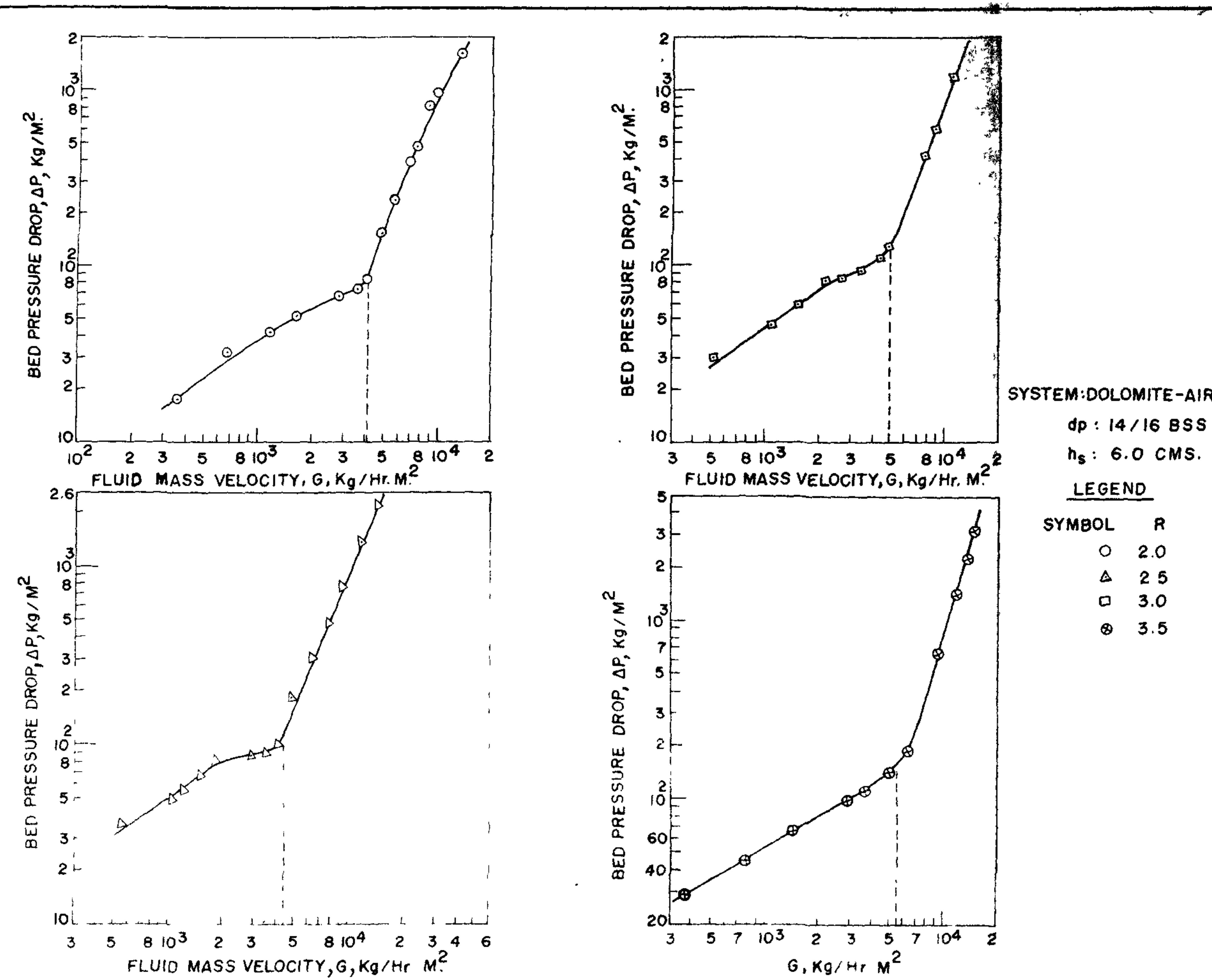


FIG. 5 B11 EFFECT OF BED EXPANSION RATIO ON THE ONSET OF SEMI-FLUIDIZATION VELOCITY.

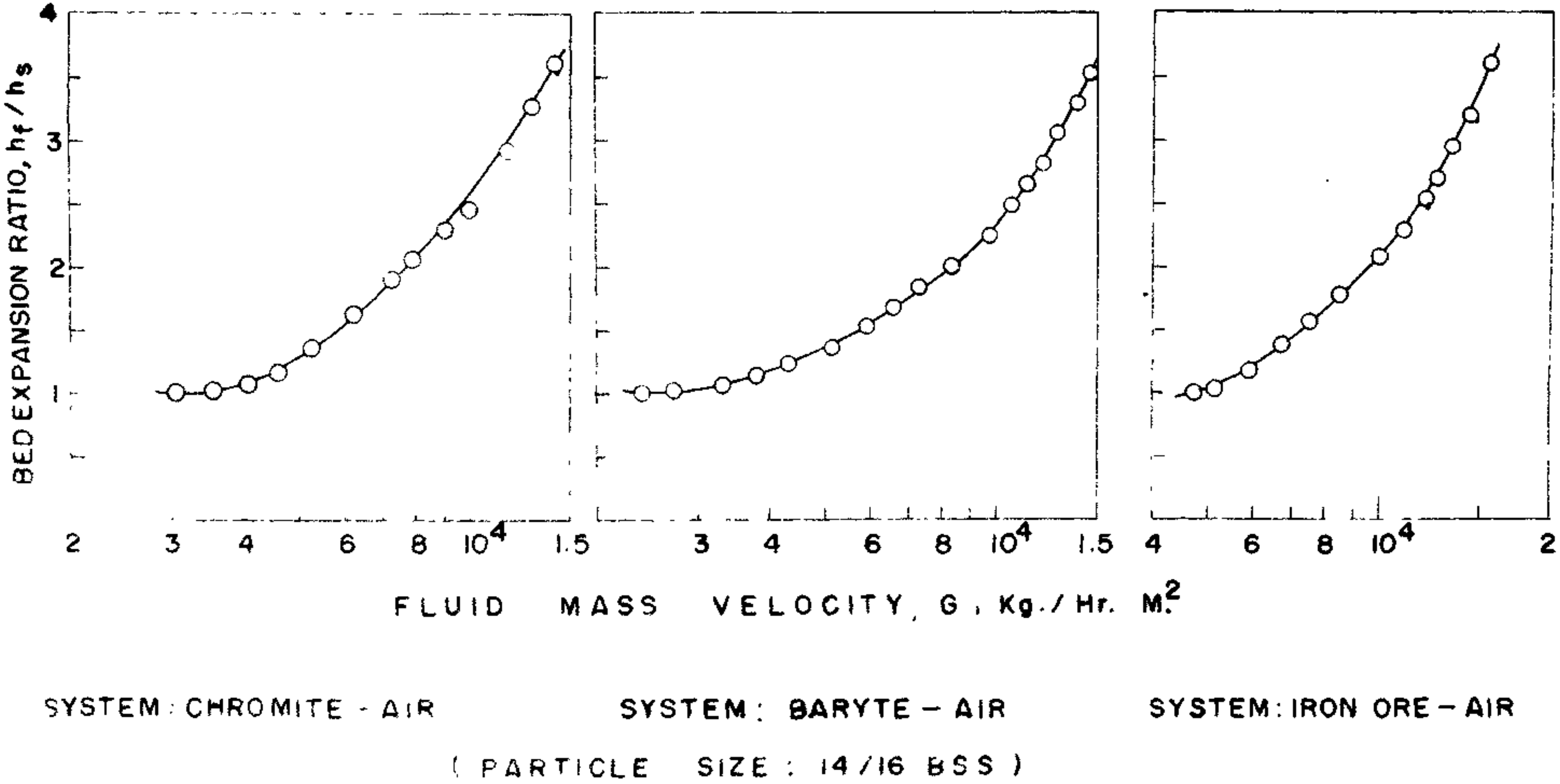


FIG. 5 B_{12} PREDICTION OF MINIMUM SEMI-FLUIDIZATION VELOCITY FROM BED EXPANSION DATA.

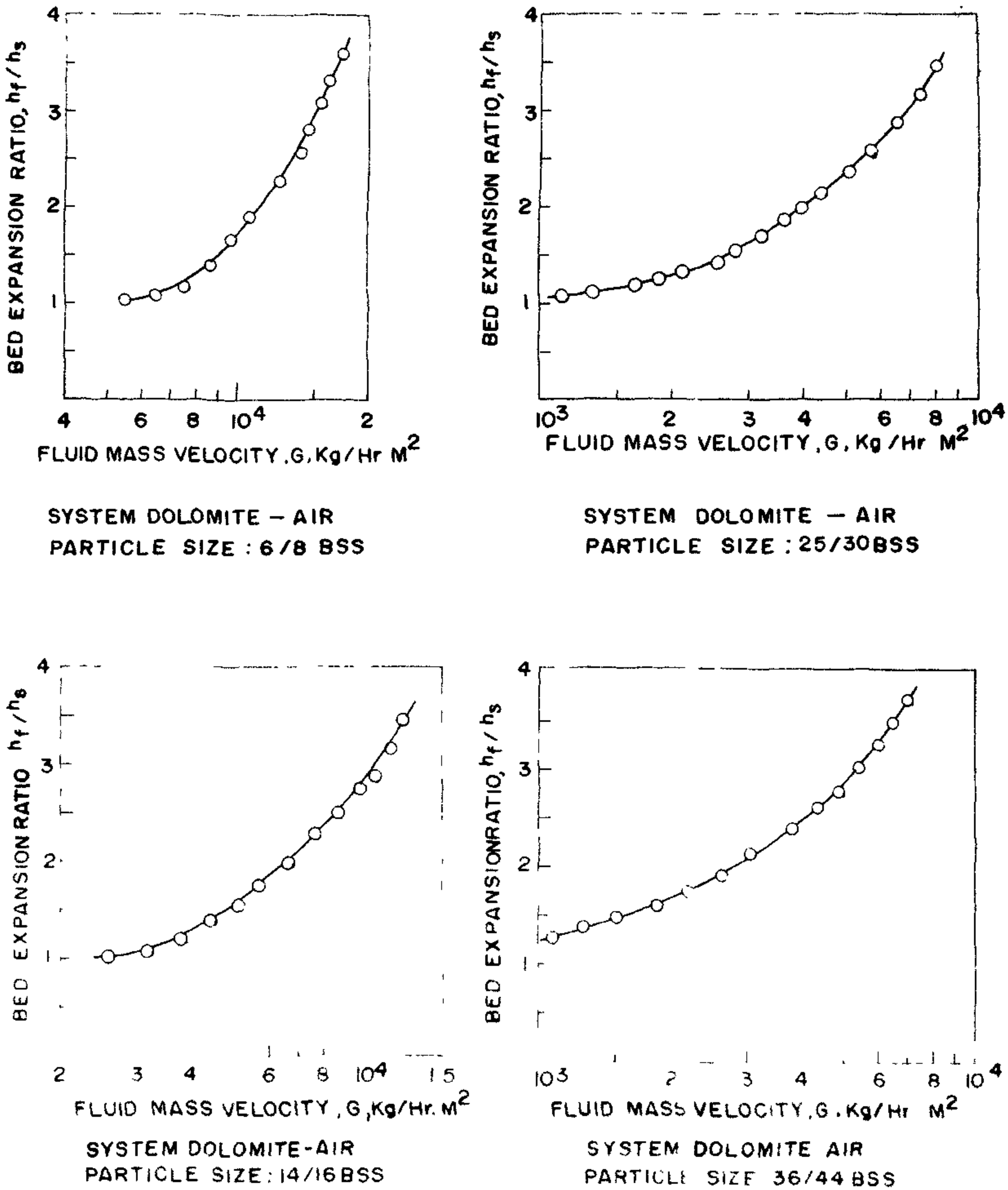
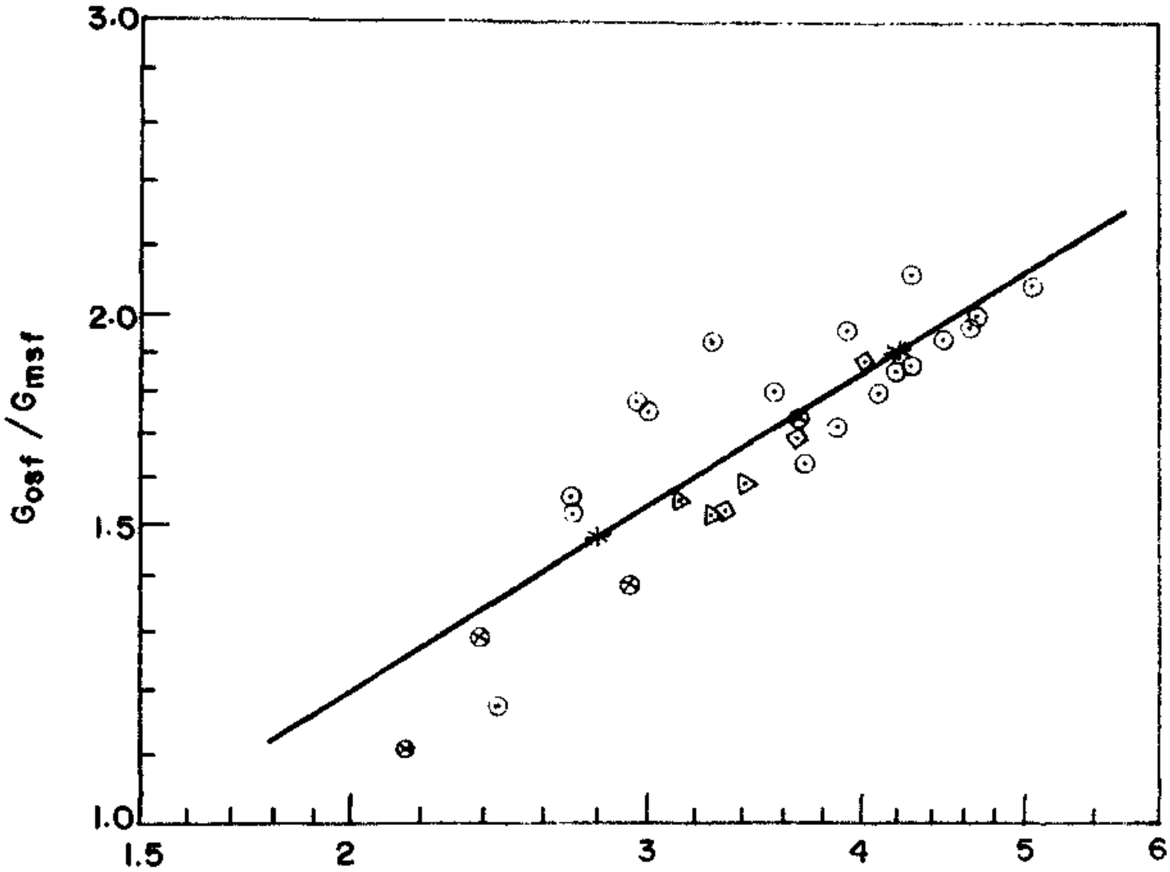


FIG. 5. B_{13} PREDICTION OF MINIMUM SEMI – FLUIDIZATION VELOCITY FROM BED EXPANSION DATA



PROD.

$$\left(\frac{D_c}{d_p}\right)^{-0.292} \left(\frac{\rho_s}{\rho_f}\right)^{0.248} R^{0.651}$$

LEGEND

⊗ D_c / d_p

△ ρ_s / ρ_f

⊡ R

⊙ OTHER EXPT. POINTS

✱ CORRELATION POINTS (BY LEAST SQUARE METHOD)

FIG. 5.B_{14} RELATION OF G_{osf} / G_{msf} WITH SYSTEM VARIABLES.

C H A P T E R - VI

PREDICTION OF PACKED BED FORMATION

** The tables and figures referred in the text have been given at the end of the chapter .

PREDICTION OF PACKED BED FORMATION

While it is necessary to know the velocity at which semi-fluidization begins and also the velocity at which all the particles are transferred to the packed section below the top restraint, it is also necessary to know the variation of the height of the packed bed with change in the velocity of the fluid, the two limits of the velocity being the onset of semi-fluidization and the maximum semi-fluidization velocity. This is of importance, especially in the design of mixed and tubular reactor system, where a knowledge of the relative distribution of particles in the two sections of the bed namely the packed and the fluidized sections, is essential.

The various methods available for the prediction of packed bed formation have been discussed in detail in Chapter-II.

All these methods directly relate the packed bed formed below the restraint to G_{sf} either through G_{osf} or G_{msf}. The system parameters like the column diameter, particle diameter, bed expansion ratio etc. have not been considered and hence an attempt has been made in this section to develop a correlation for the prediction of semi-fluidization velocity as a function of packed bed formation and other system parameters.

The parameter of importance in this case are :

$$\frac{G_{sf}}{G_{msf}}, \quad \frac{D_c}{d_p}, \quad \frac{\rho_s}{\rho_f}, \quad R \text{ and } \frac{h_{pa}}{h_s} .$$

The relation can be written as -

$$\frac{G_{sf}}{G_{msf}} = \Psi \left[\frac{D_c}{d_p}, \ \frac{\rho_s}{\rho_f}, \ R, \ \frac{h_{pa}}{h_s} \right] \qquad \ldots \qquad (6.1)$$

or,

$$\frac{G_{sf}}{G_{msf}} = A \ \left(\frac{D_c}{d_p}\right)^{a_1} \left(\frac{\rho_s}{\rho_f}\right)^{a_2} (R)^{a_3} \left(\frac{h_{pa}}{h_s}\right)^{a_4} \qquad \ldots \qquad (6.2)$$

where, A is a constant and a_1, a_2, a_3 and a_4 are exponents of the system variables. The effect of individual parameters can be seen from tables-6.A_1 and 6.B_1. The exponents have been evaluated by plotting G_{sf}/G_{msf} against each of the system variables on log - log coordinates for both liquid- solid and gas-solid systems. After substitution of the exponents, equation (6.2) becomes,

for liquid-solid system,

$$\frac{G_{sf}}{G_{msf}} = A \left[\left(\frac{D_c}{d_p}\right)^{-0.224} \left(\frac{\rho_s}{\rho_f}\right)^{-0.179} (R)^{0.630} \left(\frac{h_{pa}}{h_s}\right)^{0.470} \right]^{B} \qquad \ldots \qquad (6.3A)$$

for gas-solid system,

$$\frac{G_{sf}}{G_{msf}} = A' \left[\left(\frac{D_c}{d_p}\right)^{-0.206} \left(\frac{\rho_s}{\rho_f}\right)^{-0.372} (R)^{0.972} \left(\frac{h_{pa}}{h_s}\right)^{0.707} \right]^{B'} \qquad \ldots \qquad (6.3B)$$

where, A and A' are the coefficients and B and B' are the exponents of the overall product (Prod.). So equation (6.3) can be written as -

$$\frac{G_{sf}}{G_{msf}} = A \ (\text{Prod.})^{B} \qquad \ldots \qquad \ldots \qquad (6.4)$$

The products have been calculated and presented in tables- 6.A_2 and 6.B_2. The ratio of G_{sf}/G_{msf} is plotted on log- log coordinates against the products $\left(\frac{D_c}{d_p}\right)^{-0.224}\left(\frac{\rho_s}{\rho_f}\right)^{-0.179}(R)^{0.630}$ $\left(\frac{h_{pa}}{h_s}\right)^{0.470}$ and $\left(\frac{D_c}{d_p}\right)^{-0.206}\left(\frac{\rho_s}{\rho_f}\right)^{-0.372}(R)^{0.972}\left(\frac{h_{pa}}{h_s}\right)^{0.714}$ in figs.- 6.A_1 and 6.B_1 respectively. Two straight lines have been obtained, the equations for which can be written as follows:

For liquid- solid system,

$$\frac{G_{sf}}{G_{msf}} = 0.925\left(\frac{D_c}{d_p}\right)^{-0.15}\left(\frac{\rho_s}{\rho_f}\right)^{-0.12}(R)^{0.43}\left(\frac{h_{pa}}{h_s}\right)^{0.32} \quad \ldots \quad (6.5A)$$

and for gas- solid system,

$$\frac{G_{sf}}{G_{msf}} = 4.80\left(\frac{D_c}{d_p}\right)^{-0.18}\left(\frac{\rho_s}{\rho_f}\right)^{-0.32}(R)^{0.81}\left(\frac{h_{pa}}{h_s}\right)^{0.59} \quad \ldots \quad (6.5B)$$

Equation (6.5) gives the values of semi-fluidization velocity (in terms of G_{sf}/G_{msf}) for a desired packed bed formation.

The values of semi-fluidization velocity have been calculated with the help of equations (6.5A) and (6.5B) for a number of cases and have been compared with the experimental values for the same packed bed formations in table- 6.A_3 (for liquid- solid system) and in table- 6.B_3 (for gas- solid system). More than 170 experimental points have also been compared with the calculated values of semi-fluidization velocity in fig.- 6.A_2 for liquid- solid systems. In fig.- 6.B_2, about 150 experimental points for gas-solid systems have been presented. The results compare within 15-20% in most of the cases excepting that of the coarsest size of dolomite particles . This can be attributed to the fact that the particles being coarser, the packed bed formation is dependant upon the orientation of the particles and also because of the higher gas mass velocity involved there is larger compaction of bed than in the case of smaller size particles and also at lower values of gas mass velocity.

The material balance approach for the calculation of packed bed formation in semi- fluidization has not been adopted in the present study, because it was observed earlier that, the values calculated by the above method deviate widely from the experimental values especially in the initial and the final stages of the semi- fluidization operation. This is because the exact measurement of expanded bed height (and hence expanded bed voidage) presents considerable difficulty in liquid - fluidized bed and more so in the gas- fluidized system. Any small error in expanded bed porosity measurement will be magnified in the final calculated values. Fan et-al[1] have reported that the observed and calculated values of packed bed heights tallied well upto a value of $\epsilon_f = 0.8$.

Reference

1. Fan, L.T., Yang, Y.C. and Wen, C.Y., A.I.Ch.E.Jl., 5, 407, (1959).

Nomenclature

D_c = Diameter of the column (semifluidizer), L

d_p = Particle diameter, L

G_{msf} = Maximum semi-fluidization mass velocity, $ML^{-2}\,\theta^{-1}$

G_{sf} = Semi-fluidization mass velocity, $ML^{-2}\,\theta^{-1}$

h_{pa} = Height of packed section in semi-fluidization, L

h_s = Height of initial static bed, L

R = Bed expansion ratio in semi-fluidization, dimensionless.

ρ_s = Density of solid, ML^{-3}

ρ_f = Density of fluid, ML^{-3}

ψ = Function

ϵ_f = Porosity of fluidized bed or fluidized section of semifluidized bed, dimensionless.

TABLE- 6.A1

Effect of various system parameters on the ratio of semi-fluidization to the maximum semi-fluidization velocities.

(a) Influence of wall-effect :-

Sl. No.	Operating parameter D_c/d_p	G_{sf}/G_{msf}	Constant parameters
1.	10.42	0.565	$\rho_s/\rho_f = 2.83$
2.	23.00	0.465	$R = 2.00$
3.	46.15	0.420	$h_s/D_c = 2.36$
4.	65.50	0.380	$h_{pa}/h_s = 0.50$
5.	93.00	0.338	

(b) Influence of density ratio :-

Sl. No.	Operating parameter, ρ_s/ρ_f	G_{sf}/G_{msf}	Constant parameters
1.	2.83	0.465	$R = 2.00$
2.	3.72	0.521	$h_s/D_c = 2.36$
3.	4.45	0.506	$h_{pa}/h_s = 0.50$
4.	5.25	0.497	$D_c/d_p = 23.0$
5.	2.83	0.380	$R = 2.00$
6.	3.72	0.453	$h_s/D_c = 2.36$
7.	4.45	0.445	$h_{pa}/h_s = 0.50$
8.	5.25	0.428	$D_c/d_p = 65.50$

Contd...

TABLE- 6.A_1 (Contd.)

(c) Influence of bed expansion ratio :-

Sl. No.	Operating parameter, R	G_{sf}/G_{msf}	Constant parameters
1.	2.0	0.465	D_c/d_p = 23.0
2.	2.5	0.525	h_s/D_c = 2.36
3.	3.0	0.577	ρ_s/ρ_f = 2.83
4.	3.5	0.597	h_{pa}/h_s = 0.50
5.	2.0	0.380	D_c/d_p = 65.50
6.	2.5	0.432	h_s/D_c = 2.36
7.	3.0	0.504	$_s/\ _f$ = 2.83
8.	3.5	0.551	h_{pa}/h_s = 0.50

(d) Influence of packed bed formation :-

Sl. No.	operating parameter, h_{pa}/h_s	G_{sf}/G_{msf}	Constant parameters
1.	0.250	0.388	
2.	0.400	0.443	ρ_s/ρ_f = 2.83
3.	0.500	0.465	R = 2.00
4.	0.666	0.522	h_s/D_c = 2.36
5.	0.800	0.572	D_c/d_p =23.00
6.	0.917	0.666	
7.	0.200	0.293	
8.	0.300	0.338	ρ_s/ρ_f = 2.83
9.	0.500	0.380	R = 2.00
10.	0.733	0.469	h_s/D_c = 2.36
11.	0.833	0.560	D_c/d_p =65.50
12.	0.917	0.670	

TABLE- 6.B_1

Effect of various system parameters on the ratio of semi-fluidization to maximum semi-fluidization velocities.

Sl. No.	Operating parameter, D_c/d_p	G_{sf}/G_{msf}	Constant parameters
(a) Influence of wall effect -			
1.	18.10	0.277	ρ_s/ρ_f = 1210.0
2.	39.80	0.270	R = 2.0
3.	80.00	0.235	h_s/D_c = 1.363
4.	113.30	0.207	h_{pa}/h_s = 0.50

Sl. No.	Operating parameter ρ_s/ρ_f	G_{sf}/G_{msf}	Constant parameters
(b) Influence of density ratio -			
1.	1210.0	0.270	D_c/d_p = 39.80
2.	1590.0	0.246	R = 2.0
3.	1900.0	0.222	h_s/D_c = 1.363
4.	2244.0	0.214	h_{pa}/h_s = 0.50

Sl. No.	Operating parameter, R	G_{sf}/G_{msf}	Constant parameters
(c) Bed expansion ratio -			
1.	2.0	0.270	D_c/d_p = 39.80
2.	2.5	0.325	h_s/D_c = 1.363
3.	3.0	0.397	ρ_s/ρ_f = 1210.0
4.	3.5	0.470	h_{pa}/h_s = 0.50

Contd...

TABLE- $6.B_1$ (Contd.)

Sl. No.	Operating parameter h_{pa}/h_s	G_{sf}/G_{msf}	Constant parameters
(d) Influence of packed bed formation -			
1.	0.200	0.171	ρ_s/ρ_f = 1210.0
2.	0.300	0.204	
3.	0.400	0.244	D_c/d_p = 39.80
4.	0.500	0.270	R = 2.0
5.	0.600	0.311	h_s/D_c = 1.363
6.	0.700	0.348	
7.	0.866	0.472	

T A B L E- 6.A_2

Relation of velocity ratio (G_{sf}/G_{msf}) with system variables.

Sl. No.	$\frac{D_c}{d_p}$	ρ_s/ρ_f	R	$\frac{h_{pa}}{h_s}$	Prod.	G_{msf} $\frac{Kg}{Hr.M^2}$	G_{sf} $\frac{Kg}{Hr.M^2}$	$\frac{G_{sf}}{G_{msf}}$
1	2	3	4	5	6	7	8	9
1.	10.42	2.83	2.0	0.500	0.5487	815000	460000	0.565
2.	23.00	2.83	2.0	0.500	0.4597	620000	288200	0.465
3.	46.15	2.83	2.0	0.500	0.3933	390000	164000	0.420
4.	65.50	2.83	2.0	0.500	0.3641	310000	117500	0.380
5.	93.00	2.83	2.0	0.500	0.3362	225000	76000	0.338
6.	23.00	3.72	2.0	0.500	0.4375	700000	365000	0.521
7.	23.00	4.45	2.0	0.500	0.4237	800000	405000	0.506
8.	23.00	5.25	2.0	0.500	0.4120	975000	485000	0.497
9.	23.00	2.83	2.5	0.500	0.5290	620000	325000	0.525
10.	23.00	2.83	3.0	0.500	0.5934	620000	358000	0.577
11.	23.00	2.83	3.5	0.500	0.6534	620000	370000	0.597
12.	23.00	2.83	2.0	0.250	0.3320	620000	241000	0.388
13.	23.00	2.83	2.0	0.400	0.4139	620000	274500	0.443
14.	23.00	2.83	2.0	0.666	0.5259	620000	324000	0.522
15.	23.00	2.83	2.0	0.800	0.5733	620000	355000	0.572
16.	23.00	2.83	2.0	0.917	0.6113	620000	413000	0.666

Contd..

T A B L E- 6.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
17.	65.50	3.72	2.0	0.500	0.3466	320000	145000	0.453
18.	65.50	4.45	2.0	0.500	0.3356	390000	173800	0.445
19.	65.50	5.25	2.0	0.500	0.3265	450000	192500	0.428
20.	65.50	2.83	2.5	0.500	0.4189	310000	134000	0.432
21.	65.50	2.83	3.0	0.500	0.4699	310000	156000	0.504
22.	65.50	2.83	3.5	0.500	0.5174	310000	171000	0.551
23.	65.50	2.83	2.0	0.200	0.2368	310000	90850	0.293
24.	65.50	2.83	2.0	0.300	0.2864	310000	104800	0.338
25.	65.50	2.83	2.0	0.733	0.4358	310000	145100	0.469
26.	65.50	2.83	2.0	0.833	0.4628	310000	173800	0.560
27.	65.50	2.83	2.0	0.917	0.4842	310000	207500	0.670
28.	10.42	2.83	2.0	0.333	0.4532	815000	440500	0.541
29.				0.600	0.5977		494000	0.605
30.				0.750	0.6638		535000	0.656
31.				0.883	0.7168		582000	0.715
32.			2.5	0.333	0.5214		514000	0.630
33.				0.600	0.6876		549000	0.674
34.				0.700	0.7394		582000	0.715
35.				0.800	0.7873		618000	0.758
36.				0.850	0.8100		651000	0.800
37.			3.0	0.300	0.5571		549000	0.674
38.				0.550	0.7405		582000	0.715
39.				0.700	0.8295		618000	0.758
40.				0.850	0.9087		685000	0.840

Contd...

TABLE- $6.A_2$ (Contd.)

1	2	3	4	5	6	7	8	9
41.	10.42	2.83	3.5	0.300	0.6134	815000	576000	0.706
42.				0.450	0.7420		604500	0.741
43.				0.633	0.8710		651000	0.800
44.				0.833	0.9911		685000	0.840
45.				0.950	1.0543		774000	0.950
46.	23.00	2.83	2.5	0.150	0.3003	620000	248000	0.400
47.				0.266	0.3931		274500	0.443
48.				0.416	0.4849		309000	0.499
49.				0.600	0.5761		343500	0.554
50.				0.750	0.6398		379000	0.611
51.				0.900	0.6971		446000	0.720
52.			3.0	0.284	0.4553		317000	0.511
53.				0.416	0.5440		343500	0.554
54.				0.600	0.6463		379000	0.611
55.				0.750	0.7178		413000	0.665
56.				0.917	0.7890		480000	0.774
57.			3.5	0.333	0.5397		343500	0.554
58.				0.550	0.6832		379000	0.611
59.				0.666	0.7474		413000	0.665
60.				0.800	0.8149		446000	0.720
61.				0.917	0.8688		514000	0.828

Contd..

TABLE- 6.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
62.	46.15	2.83	2.0	0.125	0.2048	390000	117500	0.301
63.				0.416	0.3606		152000	0.390
64.				0.583	0.4227		173800	0.445
65.				0.750	0.4758		207500	0.531
66.				0.866	0.5091		248000	0.635
67.			2.5	0.125	0.2356		145100	0.372
68.				0.400	0.4074		173800	0.445
69.				0.600	0.4929		207500	0.531
70.				0.800	0.5643		241000	0.618
71.				0.917	0.6017		274500	0.705
72.			3.0	0.166	0.3023		173800	0.445
73.				0.466	0.4908		207500	0.531
74.				0.733	0.6076		241000	0.618
75.				0.850	0.6514		274500	0.705
76.				0.933	0.6805		309000	0.792
77.			3.5	0.125	0.2911		185700	0.476
78.				0.375	0.4881		207500	0.531
79.				0.633	0.6244		241000	0.618
80.				0.800	0.6972		274500	0.705
81.				0.883	0.7303		309000	0.792
82.				0.966	0.7617		343500	0.880

Contd..

TABLE- 6.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
83.	65.50	2.83	2.5	0.150	0.2379	310000	104800	0.338
84.				0.400	0.3771		124300	0.401
85.				0.600	0.4563		145100	0.468
86.				0.750	0.5068		173800	0.560
87.				0.950	0.5664		241000	0.777
88.			3.0	0.166	0.2799		124300	0.401
89.				0.416	0.4309		145100	0.468
90.				0.666	0.5376		173800	0.560
91.				0.833	0.5973		207500	0.669
92.				0.950	0.6354		274500	0.885
93.			3.5	0.100	0.2427		124300	0.401
94.				0.250	0.3738		145100	0.468
95.				0.550	0.5412		173800	0.560
96.				0.750	0.6261		207500	0.669
97.				0.866	0.6764		241000	0.777
98.	93.00	2.83	2.0	0.250	0.2428	225000	56250	0.250
99.				0.450	0.3199		71100	0.316
100.				0.600	0.3662		85000	0.378
101.				0.750	0.4067		104800	0.465
102.				0.950	0.4545		138200	0.615
103.			2.5	0.166	0.2304		71100	0.316
104.				0.400	0.3482		85000	0.378
105.				0.666	0.4425		104800	0.465
106.				0.800	0.4824		124300	0.552
107.				0.917	0.5143		145100	0.645

Contd.

1	2	3	4	5	6	7	8	9
108.	93.00	2.83	3.0	0.200	0.2822	225000	85000	0.378
109.				0.500	0.4339		104800	0.465
110.				0.666	0.4964		117500	0.522
111.				0.800	0.5412		138200	0.615
112.				0.950	0.5867		173800	0.771
113.			3.5	0.292	0.3709		96800	0.430
114.				0.550	0.4997		117500	0.522
115.				0.750	0.5781		138200	0.615
116.				0.850	0.6132		152000	0.675
117.				0.950	0.6460		185700	0.825
118.	23.00	3.72	2.0	0.300	0.3442	700000	317000	0.453
119.				0.400	0.3938		343500	0.490
120.				0.600	0.4765		379000	0.541
121.				0.733	0.5236		413000	0.590
122.				0.950	0.5915		480000	0.685
123.			2.5	0.166	0.3020		343500	0.490
124.				0.333	0.4158		379000	0.541
125.				0.500	0.5033		413000	0.590
126.				0.666	0.5758		446000	0.637
127.				0.900	0.6634		514000	0.734
128.			3.0	0.250	0.4078		393000	0.561
129.				0.333	0.4664		413000	0.590
130.				0.500	0.5646		446000	0.637
131.				0.666	0.6459		480000	0.685
132.				0.900	0.7442		549000	0,784

Contd.

T A B L E- 6.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
133.	23.00	3.72	3.5	0.150	0.3531	700000	413000	0.590
134.				0.300	0.4891		446000	0.637
135.				0.450	0.5916		480000	0.685
136.				0.600	0.6773		514000	0.734
137.				0.850	0.7978		582000	0.831
138.	23.00	4.45	2.0	0.150	0.2406	800000	309000	0.386
139.				0.250	0.3060		343500	0.429
140.				0.400	0.3814		379000	0.474
141.				0.533	0.4566		413000	0.516
142.				0.650	0.4793		446000	0.558
143.				0.850	0.5437		549000	0.685
144.			2.5	0.200	0.3170		379000	0.474
145.				0.300	0.3835		413000	0.516
146.				0.400	0.4389		446000	0.558
147.				0.500	0.4875		480000	0.600
148.				0.650	0.5515		514000	0.642
149.				0.800	0.6080		582000	0.728
150.			3.0	0.150	0.3105		413000	0.516
151.				0.250	0.3950		454500	0.568
152.				0.350	0.4623		480000	0.600
153.				0.467	0.5294		514000	0.642
154.				0.550	0.5718		549000	0.685
155.				0.666	0.6256		582000	0.728
156.				0.833	0.6951		651000	0.815

Contd..

T A B L E- 6.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
157.	23.00	4.45	3.5	0.200	0.3916	800000	468000	0.585
158.				0.300	0.4737		494000	0.617
159.				0.400	0.5421		529500	0.661
160.				0.600	0.6559		582000	0.728
161.				0.850	0.7727		685000	0.856
162.	23.00	5.25	2.0	0.200	0.2679	975000	413000	0.424
163.				0.333	0.3404		446000	0.458
164.				0.650	0.4661		549000	0.563
165.				0.750	0.4985		618000	0.634
166.				0.833	0.5237		685000	0.702
167.			2.5	0.250	0.3425		480000	0.492
168.				0.333	0.3917		514000	0.527
169.				0.416	0.4347		549000	0.563
170.				0.633	0.5296		618000	0.634
171.				0.750	0.5736		685000	0.702
172.			3.0	0.217	0.3595		514000	0.526
173.				0.400	0.4789		582000	0.597
174.				0.500	0.5319		618000	0.634
175.				0.666	0.6085		685000	0.702
176.				0.850	0.6826		715000	0.734
177.			3.5	0.200	0.3808		569000	0.584
178.				0.350	0.4951		618000	0.634
179.				0.550	0.6124		685000	0.702
180.				0.700	0.6859		711000	0.730
181.				0.850	0.7515		778000	0.798

TABLE- 6.B_2

Relation of velocity ratio (G_{sf}/G_{msf}) with system variables.

Sl. No.	$\frac{D_c}{d_p}$	ρ_s/ρ_f	R	$\frac{h_{pa}}{h_s}$	Prod.	G_{msf} (Kg/Hr.M^2)	G_{sf} (Kg/Hr.M^2)	$\frac{G_{sf}}{G_{msf}}$
1	2	3	4	5	6	7	8	9
1.	18.10	1210	2.0	0.500	0.0472	43000	11910	0.277
2.	39.80	1210	2.0	0.500	0.0403	28000	7567	0.270
3.	80.00	1210	2.0	0.500	0.0348	17000	4001	0.235
4.	113.30	1210	2.0	0.500	0.0325	14000	2900	0.207
5.	39.80	1590	2.0	0.500	0.0364	32000	7857	0.246
6.	39.80	1900	2.0	0.500	0.0339	36000	7982	0.222
7.	39.80	2244	2.0	0.500	0.0321	40000	8554	0.214
8.	39.80	1210	2.5	0.500	0.0500	28000	9113	0.325
9.	39.80	1210	3.0	0.500	0.0597	28000	11120	0.397
10.	39.80	1210	3.5	0.500	0.0693	28000	13160	0.470
11.	39.80	1210	2.0	0.200	0.0210	28000	4738	0.171
12.	39.80	1210	2.0	0.300	0.0281	28000	5725	0.204
13.	39.80	1210	2.0	0.400	0.0343	28000	6843	0.244
14.	39.80	1210	2.0	0.600	0.0458	28000	8719	0.311
15.	39.80	1210	2.0	0.700	0.0510	28000	9738	0.348
16.	39.80	1210	2.0	0.866	0.0593	28000	13226	0.472

Contd...

TABLE- 6.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
17.	18.10	1210	2.0	0.167	0.0217	43000	8330	0.194
18.				0.333	0.0355		9278	0.216
19.				0.666	0.0578		13226	0.308
20.				0.833	0.0678		15397	0.358
21.			2.5	0.200	0.0307		9146	0.213
22.				0.333	0.0441		10693	0.249
23.				0.500	0.0587		13061	0.304
24.				0.600	0.0667		15200	0.353
25.				0.666	0.0718		16779	0.390
26.			3.0	0.150	0.0299		9080	0.211
27.				0.250	0.0429		10265	0.239
28.				0.400	0.0598		13884	0.323
29.				0.500	0.0701		16779	0.390
30.				0.650	0.0842		19279	0.448
31.			3.5	0.166	0.0374		10660	0.248
32.				0.300	0.0578		13884	0.324
33.				0.400	0.0695		16450	0.383
34.				0.500	0.0813		19279	0.448
35.	39.80	1210	2.5	0.133	0.0196	28000	4738	0.171
36.				0.200	0.0261		6284	0.224
37.				0.333	0.0376		7870	0.283
38.				0.650	0.0603		11745	0.423
39.				0.833	0.0718		14443	0.520

Contd..

TABLE- 6.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
40.	39.80	1210	3.0	0.200	0.0312	28000	7633	0.275
41.				0.333	0.0449		8751	0.315
42.				0.666	0.0731		13555	0.488
43.				0.766	0.0807		15035	0.541
44.			3.5	0.200	0.0362		9107	0.328
45.				0.333	0.0521		11449	0.412
46.				0.666	0.0849		14737	0.531
47.	80.00	1210	2.0	0.150	0.0149	17000	2764	0.163
48.				0.300	0.0243		3158	0.186
49.				0.650	0.0420		5310	0.312
50.				0.800	0.0486		6922	0.407
51.				0.900	0.0528		9107	0.535
52.			2.5	0.166	0.0199		3211	0.189
53.				0.333	0.0325		3705	0.218
54.				0.500	0.0433		5047	0.297
55.				0.650	0.0521		6593	0.388
56.				0.750	0.0577		8317	0.490
57.				0.900	0.0656		10364	0.609
58.			3.0	0.166	0.0238		3705	0.218
59.				0.250	0.0317		4461	0.262
60.				0.400	0.0441		5422	0.319
61.				0.500	0.0517		6705	0.394
62.				0.666	0.0633		8883	0.522
63.				0.866	0.0762		10923	0.644

Contd..

TABLE- 6.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
64.	80.00	1210	3.5	0.200	0.0313	17000	4724	0.278
65.				0.333	0.0451		6685	0.393
66.				0.500	0.0600		7501	0.441
67.				0.633	0.0709		9278	0.546
68.				0.800	0.0837		10923	0.643
69.				0.900	0.0909		12699	0.747
70.	113.30	1210	2.0	0.250	0.0199	14000	1908	0.136
71.				0.400	0.0277		2290	0.164
72.				0.666	0.0398		3619	0.258
73.				0.750	0.0432		4724	0.337
74.				0.850	0.0472		5633	0.402
75.				0.900	0.0492		6685	0.476
76.			2.5	0.100	0.0129		1744	0.125
77.				0.200	0.0211		1974	0.141
78.				0.333	0.0303		2836	0.203
79.				0.500	0.0403		3685	0.263
80.				0.616	0.0467		4461	0.319
81.				0.700	0.0511		5409	0.386
82.				0.800	0.0562		6514	0.465
83.				0.883	0.0603		7383	0.526
84.			3.0	0.166	0.0220		2764	0.197
85.				0.350	0.0374		3586	0.256
86.				0.500	0.0481		4395	0.314
87.				0.600	0.0547		5304	0.379
88.				0.700	0.0610		7021	0.501
89.				0.833	0.0690		7962	0.569

TABLE- 6.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
90.	113.30	1210	3.5	0.166	0.0257	14000	3126	0.223
91.				0.333	0.0420		4395	0.314
92.				0.500	0.0559		5297	0.378
93.				0.600	0.0636		6416	0.458
94.				0.750	0.0745		8087	0.578
95.	39.80	1590	2.0	0.166	0.0168	32000	5593	0.175
96.				0.300	0.0254		6462	0.202
97.				0.750	0.0485		9738	0.304
98.				0.850	0.0529		13292	0.415
99.			2.5	0.200	0.0236		6297	0.197
100				0.250	0.0277		6797	0.212
101.				0.417	0.0398		8396	0.262
102.				0.500	0.0453		9442	0.295
103.				0.600	0.0515		11351	0.355
104.				0.800	0.0631		14673	0.458
105.			3.0	0.183	0.0266		7041	0.220
106.				0.250	0.0331		7949	0.248
107.				0.400	0.0461		9080	0.284
108.				0.500	0.0540		11416	0.357
109.				0.666	0.0662		14147	0.442
110.				0.750	0.0720		15924	0.498

Contd..

TABLE- 6.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
111.	39.80	1590	3.5	0.166	0.0289	32000	8390	0.262
112.				0.250	0.0384		9028	0.282
113.				0.400	0.0535		11416	0.357
114.				0.500	0.0627		13226	0.413
115.				0.600	0.0713		14838	0.464
116.				0.750	0.0835		17536	0.548
117.	39.80	1900	2.0	0.200	0.0177	36000	5922	0.165
118.				0.250	0.0207		6304	0.175
119.				0.450	0.0314		7501	0.208
120.				0.700	0.0429		10857	0.302
121.				0.800	0.0472		13061	0.363
122.			2.5	0.250	0.0258		7238	0.201
123.				0.400	0.0360		8212	0.228
124.				0.500	0.0421		10035	0.279
125.				0.650	0.0507		13292	0.369
126.				0.750	0.0561		14970	0.416
127.			3.0	0.200	0.0263		7685	0.213
128.				0.300	0.0351		8975	0.249
129.				0.400	0.0429		10199	0.283
130.				0.500	0.0503		11712	0.325
131.				0.600	0.0572		13489	0.375
132.				0.700	0.0638		15924	0.442

Contd..

T A B L E- 6.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
133.	39.80	1900	3.5	0.200	0.0305	36000	9100	0.253
134.				0.250	0.0357		9212	0.256
135.				0.400	0.0498		12041	0.334
136.				0.500	0.0584		14443	0.401
137.				0.600	0.0664		16450	0.457
138.	39.80	2244	2.0	0.200	0.0168	40000	6922	0.173
139.				0.400	0.0274		7975	0.199
140.				0.700	0.0407		11515	0.288
141.				0.833	0.0460		13555	0.339
142.			2.5	0.200	0.0209		7389	0.185
143.				0.400	0.0340		9015	0.225
144.				0.500	0.0399		10364	0.259
145.				0.650	0.0480		13654	0.341
146.				0.750	0.0531		15660	0.391
147.			3.0	0.166	0.0219		8212	0.205
148.				0.250	0.0291		9317	0.233
149.				0.400	0.0406		11186	0.280
150.				0.500	0.0476		14147	0.354
151.				0.650	0.0573		15891	0.397
152.			3.5	0.166	0.0254		8883	0.222
153.				0.333	0.0415		11186	0.280
154.				0.450	0.0512		13028	0.326
155.				0.500	0.0552		14673	0.367
156.				0.600	0.0628		16615	0.415

T A B L E- 6.A_3

Comparison of the values of semi-fluidization velocities.

Run No.	$\frac{h_{pa}}{h_s}$	G_{sf}, Kg./Hr.M^2 Calculated	Experimental	Percentage deviation of calculated values from the experimental values.
1	2	3	4	5
$LSP/D/d_{p_1}/h_{s_1}/R_1$	0.333	503711	440500	+14.35
	0.500	573478	460000	+24.67
	0.600	607853	494000	+23.05
	0.750	652948	535000	+22.05
	0.883	688063	582000	+18.22
$LSP/D/d_{p_1}/h_{s_1}/R_2$	0.333	554627	514000	+ 7.90
	0.600	669211	549000	+21.90
	0.700	703217	582000	+20.83
	0.800	733896	618000	+18.75
	0.850	748312	651000	+14.95
$LSP/D/d_{p_1}/h_{s_1}/R_3$	0.300	579946	549000	+ 5.64
	0.550	704234	582000	+21.00
	0.700	760602	618000	+23.07
	0.850	809393	685000	+18.16
$LSP/D/d_{p_1}/h_{s_1}/R_4$	0.300	619774	576000	+ 7.60
	0.450	705435	604500	+16.70
	0.633	787030	651000	+24.25
	0.833	859293	685000	+25.44
	0.950	896163	774000	+15.78

Contd...

TABLE- 6.A_3 (Contd.)

1	2	3	4	5
$LSP/D/d_{p_2}/h_{s_1}/R_1$	0.250	243225	241000	+ 0.92
	0.400	282622	274500	+ 2.96
	0.500	303534	288200	+ 5.32
	0.666	332723	324000	+ 2.69
	0.800	352863	355000	- 0.60
	0.917	368589	413000	-10.75
$LSP/D/d_{p_2}/h_{s_1}/R_2$	0.150	227278	248000	- 8.36
	0.266	273076	274500	- 0.52
	0.416	315122	309000	+ 1.98
	0.500	334213	325000	+ 2.83
	0.600	354243	343500	+ 3.13
	0.750	380563	379000	+ 0.41
	0.900	403406	446000	- 9.55
$LSP/D/d_{p_2}/h_{s_1}/R_3$	0.284	301493	317000	- 4.89
	0.416	340835	343500	- 0.78
	0.500	361471	358000	+ 0.97
	0.600	383156	379000	+ 1.10
	0.750	411573	413000	- 0.35
	0.916	438941	480000	- 8.55
$LSP/D/d_{p_2}/h_{s_1}/R_4$	0.333	339290	343500	- 1.23
	0.500	386301	370000	+ 4.41
	0.550	398330	379000	+ 5.10
	0.666	423436	413000	+ 2.53
	0.800	449039	446000	+ 0.68
	0.916	469068	514000	- 8.74

Contd.

T A B L E- 6.A_3 (Contd.)

1	2	3	4	5
LSP/D/d_{p_3}/h_{s_1}/R_1	0.125	111577	117500	- 5.04
	0.416	163926	152000	+ 7.85
	0.500	173891	164000	+ 6.03
	0.583	182663	173800	+ 5.10
	0.750	197996	207500	- 4.58
	0.866	207329	248000	-16.40
LSP/D/d_{p_3}/h_{s_1}/R_2	0.125	122840	145100	-15.34
	0.400	178242	173800	+ 2.56
	0.600	202908	207500	- 2.21
	0.800	222522	241000	- 7.67
	0.917	232416	274500	-15.33
LSP/D/d_{p_3}/h_{s_1}/R_3	0.166	145401	173800	-16.34
	0.466	202452	207500	- 2.43
	0.733	234030	241000	- 2.89
	0.850	245398	274500	-10.60
	0.933	252802	309000	-18.19
LSP/D/d_{p_3}/h_{s_1}/R_4	0.125	141962	185700	-23.55
	0.375	201715	207500	- 2.79
	0.633	238627	241000	- 0.98
	0.800	257188	274500	- 6.31
	0.883	265433	309000	-14.10
	0.966	273152	343500	-20.48

Contd..

TABLE- 6.A_3 (Contd.)

1	2	3	4	5
LSP/D/d_{p_4}/h_{s_1}/R_1	0.200	98038	90850	+ 7.91
	0.300	111612	104800	+ 6.50
	0.500	131415	117500	+11.84
	0.733	148537	145100	+ 2.37
	0.833	154738	173800	-10.97
	0.917	159570	207500	-23.10
LSP/D/d_{p_4}/h_{s_1}/R_2	0.150	98401	104800	- 6.11
	0.400	134711	124300	+ 8.38
	0.500	144683	134000	+ 7.97
	0.600	153341	145100	+ 5.68
	0.750	164737	173800	- 5.21
	0.950	177697	241000	-26.27
LSp/D/d_{p_4}/h_{s_1}/R_3	0.166	109908	124300	-11.58
	0.416	147559	145100	+ 1.69
	0.500	156497	156000	+ 0.32
	0.666	171552	173800	- 1.29
	0.833	184289	207500	-11.19
	0.950	192193	274500	-39.67
LSP/D/d_{p_4}/h_{s_1}/R_4	0.100	99909	124300	-19.62
	0.250	133985	145100	- 7.66
	0.500	167223	171000	- 2.21
	0.550	172446	173800	- 0.78
	0.750	190406	207500	- 8.24
	0.866	199399	241000	-17.26

Contd..

T A B L E- 6.A_3 (Contd.)

1	2	3	4	5
$LSP/D/d_{p_5}/h_{s_1}/R_1$	0.250	79416	56250	+41.18
	0.450	95824	71100	+34.77
	0.500	99115	76000	+30.41
	0.600	105073	85000	+23.62
	0.750	112855	104800	+ 7.69
	0.950	121726	138200	-11.92
$LSP/D/d_{p_5}/h_{s_1}/R_2$	0.166	76637	71100	+ 7.79
	0.400	101605	85000	+19.54
	0.666	119614	104800	+14.14
	0.800	126861	124300	+ 2.06
	0.917	132509	145100	- 8.68
$LSP/D/d_{p_5}/h_{s_1}/R_3$	0.200	88043	85000	+ 3.58
	0.500	118035	104800	+12.63
	0.666	129374	117500	+10.11
	0.800	137200	138200	- 0.72
	0.950	144959	173800	-16.59
$LSP/D/d_{p_5}/h_{s_1}/R_4$	0.292	106185	96800	+ 9.70
	0.550	130063	117500	+10.69
	0.750	143603	138200	+ 3.91
	0.850	149495	152000	- 1.65
	0.950	154897	185700	-16.59

Contd..

TABLE- 6.A_3 (Contd.)

1	2	3	4	5
LSP/Cr./d_{p_2}/h_{s_1}/R_1	0.300	309687	317000	- 2.31
	0.400	339498	343500	-1 .17
	0.500	364580	365000	- 0.12
	0.600	386441	379000	+ 1.96
	0.733	412139	413000	- 0.21
	0.950	447775	480000	- 6.71
LSP/Cr./d_{p_2}/h_{s_1}/R_2	0.166	281932	343500	-17.92
	0.333	352587	379000	- 6.97
	0.500	401449	413000	- 2.80
	0.666	440031	446000	- 1.34
	0.900	484507	514000	- 5.74
LSP/Cr./d_{p_2}/h_{s_1}/R_3	0.250	347858	393000	-11.49
	0.333	381369	413000	- 7.66
	0.500	434138	446000	- 2.66
	0.666	475872	480000	- 0.86
	0.900	523980	549000	- 4.56
LSP/Cr./d_{p_2}/h_{s_1}/R_4	0.150	315512	413000	-23.60
	0.300	394048	446000	-12.58
	0.450	448460	480000	- 6.57
	0.600	491771	514000	- 4.32
	0.850	549885	582000	- 5.52

Contd..

TABLE- 6.A_3 (Contd.)

1	2	3	4	5
LSP/Ba./d_{p_2}/h_{s_1}/R_1	0.150	277187	309000	-10.30
	0.250	326590	343500	- 4.92
	0.400	379510	379000	+ 0.13
	0.500	407651	405000	+ 0.65
	0.533	416094	413000	+ 0.75
	0.650	443296	446000	- 0.61
	0.850	483163	549000	-11.99
LSP/Ba./d_{p_2}/h_{s_1}/R_2	0.200	334720	379000	-11.68
	0.300	381152	413000	- 7.71
	0.400	417813	446000	- 6.32
	0.500	448768	480000	- 6.51
	0.650	488009	514000	- 5.06
	0.800	521622	582000	-10.37
LSP/Ba./d_{p_2}/h_{s_1}/R_3	0.150	330108	415000	-20.07
	0.250	388891	454500	-14.44
	0.350	432822	480000	- 9.83
	0.467	474955	514000	- 7.60
	0.550	500516	549000	- 8.83
	0.666	532018	582000	- 8.59
	0.833	571572	651000	-12.20
LSP/Ba./d_{p_2}/h_{s_1}/R_4	0.200	386937	468000	-17.32
	0.300	440560	494000	-10.82
	0.400	482928	529500	- 8.80
	0.600	549763	582000	- 5.54
	0.850	614799	685000	-10.25

Contd..

T A B L E- 6.A_3 (Contd.)

1	2	3	4	5
$LSP/I/d_{p_2}/h_{s_1}/R_1$	0.200	335659	413000	-18.73
	0.333	395224	446000	-11.38
	0.500	449950	485000	- 7.33
	0.650	489367	549000	-10.86
	0.750	512331	618000	-17.10
	0.833	529840	685000	-22.65
$LSP/I/d_{p_2}/h_{s_1}/R_2$	0.250	396896	480000	-17.31
	0.333	435169	514000	-15.34
	0.416	467018	549000	-14.93
	0.633	534239	618000	-13.55
	0.750	563977	685000	-17.67
$LSP/I/d_{p_2}/h_{s_1}/R_3$	0.217	410357	514000	-20.16
	0.400	498869	582000	-14.28
	0.500	535823	618000	-13.30
	0.666	587293	685000	-14.26
	0.850	635069	715000	-11.18
$LSP/I/d_{p_2}/h_{s_1}/R_4$	0.200	427074	569000	-24.95
	0.350	510571	618000	-17.38
	0.550	590373	685000	-13.81
	0.700	637620	711000	-10.32
	0.850	678621	778000	-12.77

TABLE- 6.B3

Comparison of the values of semi-fluidization velocities.

Run No.	$\frac{h_{pa}}{h_s}$	G_{sf}, Kg./Hr.M^2 Calculated	Experimental	Percentage deviation of calculated values from the experimental values.
1	2	3	4	5
$GSP/D/d_{p_1}/h_{s_1}/R_1$	0.166	8565	8330	+ 2.82
	0.333	12756	9278	+37.49
	0.500	16118	11910	+35.33
	0.666	18973	13226	+43.45
	0.833	21551	15397	+39.97
$GSP/D/d_{p_1}/h_{s_1}/R_2$	0.200	11374	9146	+24.36
	0.333	15197	10693	+42.12
	0.500	19157	13061	+46.67
	0.600	21229	15200	+39.66
	0.666	22518	16779	+34.20
$GSP/D/d_{p_1}/h_{s_1}/R_3$	0.150	11098	9080	+22.22
	0.250	14874	10265	+44.90
	0.400	19433	13884	+39.97
	0.500	22058	16779	+31.41
	0.650	25604	19279	+32.81
$GSP/D/d_{p_1}/h_{s_1}/R_4$	0.166	13262	10660	+24.41
	0.300	18650	13884	+34.33
	0.400	21920	16450	+33.25
	0.500	24913	19279	+29.22

Contd..

TABLE- 6.B_3 (Contd.)

1	2	3	4	5
$GSP/D/d_{p_2}/h_{s_1}/R_1$	0.200	5014	4738	+ 5.83
	0.300	6316	5725	+10.32
	0.400	7451	6843	+ 8.88
	0.500	8449	7567	+11.66
	0.600	9390	8719	+ 7.70
	0.700	10249	9738	+ 5.25
	0.866	11551	13226	-12.66
$GSP/D/d_{p_2}/h_{s_1}/R_2$	0.133	4737	4738	- 0.02
	0.200	5983	6284	- 4.79
	0.333	7978	7870	+ 1.37
	0.500	10055	9113	+10.34
	0.650	11689	11745	- 0.48
	0.833	13462	14443	- 6.79
$GSP/D/d_{p_2}/h_{s_1}/R_3$	0.200	6897	7633	- 9.64
	0.333	9196	8751	+ 5.09
	0.500	11606	11120	+ 4.37
	0.666	13656	13555	+ 0.75
	0.766	14792	15035	- 1.62
$GSP/D/d_{p_2}/h_{s_1}/R_4$	0.200	7784	9107	-14.53
	0.333	10388	11449	- 9.27
	0.500	13102	13160	- 0.44
	0.666	15429	14739	+ 4.68

Contd..

TABLE- 6.B_3 (Contd.)

1	2	3	4	5
GSP/D/d_{p_3}/h_{s_1}/R_1	0.150	2407	2764	-12.92
	0.300	3567	3158	+12.95
	0.500	4761	4001	+19.00
	0.650	5535	5310	+ 4.24
	0.800	6237	6922	- 9.90
	0.900	6677	9107	-26.68
GSP/D/d_{p_3}/h_{s_1}/R_2	0.166	3022	3211	- 5.89
	0.333	4515	3705	+21.86
	0.500	5675	5047	+12.44
	0.650	6589	6593	-00.06
	0.750	7151	8317	-14.02
	0.900	7942	10364	-23.37
GSP/D/d_{p_3}/h_{s_1}/R_3	0.166	3496	3705	- 5.64
	0.250	4410	4461	- 1.14
	0.400	5763	5422	+ 6.29
	0.500	6554	6705	- 2.25
	0.666	7713	8883	-13.17
	0.866	8943	10923	-18.13
GSP/D/d_{p_3}/h_{s_1}/R_4	0.200	4393	4724	- 7.01
	0.333	5868	6685	-12.22
	0.500	7397	7501	- 1.39
	0.633	8469	9278	- 8.72
	0.800	9664	10923	-11.53
	0.900	10349	12699	-18.51

Contd..

T A B L E- 6.B_3 (Contd.)

1	2	3	4	5
GSP/D/d_{p_4}/h_{s_1}/R_1	0.250	2405	1908	+26.05
	0.400	3146	2290	+37.38
	0.500	3565	2900	+22.93
	0.666	4208	3619	+16.28
	0.750	4502	4724	- 4.70
	0.850	4823	5633	-14.38
	0.900	4991	6685	-25.34
GSP/D/d_{p_4}/h_{s_1}/R_2	0.100	1692	1744	- 2.98
	0.200	2516	1974	+27.46
	0.333	3369	2836	+18.79
	0.500	4250	3685	+15.33
	0.616	4781	4461	+ 7.17
	0.700	5145	5409	- 4.88
	0.800	5550	6514	-14.80
	0.883	5872	7383	-20.47
GSP/D/d_{p_4}/h_{s_1}/R_3	0.166	2614	2764	- 5.43
	0.350	3998	3586	+11.49
	0.500	4893	4395	+11.33
	0.600	5438	5304	+ 2.54
	0.700	5928	7021	-15.57
	0.833	6557	7962	-17.65

Contd..

TABLE- 6.B3 (Contd.)

1	2	3	4	5
$GSP/D/d_{p_4}/h_{s_1}/R_4$	0.166	2950	3126	- 5.63
	0.333	4390	4395	- 0.11
	0.500	5522	5297	+ 4.25
	0.600	6137	6416	- 4.35
	0.750	6962	8087	-13.91
$GSP/Cr./d_{p_2}/h_{s_1}/R_1$	0.166	4770	5593	-14.71
	0.300	6710	6462	+ 3.84
	0.500	8968	7857	+14.14
	0.750	11321	9738	+16.26
	0.850	12148	13292	- 8.61
$GSP/Cr./d_{p_2}/h_{s_1}/R_2$	0.200	6328	6297	+ 0.49
	0.250	7187	6797	+ 5.74
	0.417	9635	8396	+14.76
	0.500	10653	9442	+12.83
	0.600	11830	11351	+ 4.22
	0.800	13928	14673	- 5.08
$GSP/Cr./d_{p_2}/h_{s_1}/R_3$	0.183	6964	7041	- 1.09
	0.250	8300	7949	+ 4.42
	0.400	10844	9080	+19.43
	0.500	12307	11416	+ 7.80
	0.666	14501	14147	+ 2.50
	0.750	15518	15924	- 2.55

Contd..

TABLE- 6.B3 (Contd.)

1	2	3	4	5
$GSP/Cr./d_{p_2}/h_{s_1}/R_4$	0.166	7409	8390	-11.69
	0.250	9381	9028	+ 3.91
	0.400	12243	11416	+ 7.24
	0.500	13897	13226	+ 5.07
	0.600	15423	14838	+ 3.94
	0.750	17522	17536	- 0.08
$GSP/Ba./d_{p_2}/h_{s_1}/R_1$	0.200	5573	5922	- 5.89
	0.250	6309	6304	+ 0.08
	0.450	8833	7501	+17.76
	0.500	9358	7982	+17.24
	0.700	11356	10857	+ 4.60
	0.800	12268	13061	- 6.07
$GSP/Ba./d_{p_2}/h_{s_1}/R_2$	0.250	7501	7238	+ 3.63
	0.400	9814	8212	+19.51
	0.500	11146	10035	+11.07
	0.650	12933	13292	- 2.70
	0.750	14055	14970	- 6.11
$GSP/Ba./d_{p_2}/h_{s_1}/R_3$	0.200	7641	7685	- 0.57
	0.300	9604	8975	+ 7.01
	0.400	11321	10199	+11.00
	0.500	12828	11712	+ 9.53
	0.600	14265	13489	+ 5.75
	0.700	15562	15924	- 2.27

Contd..

TABLE- 6.B_3 (Contd.)

1	2	3	4	5
GSP/Ba./d_{p_2}/h_{s_1}/R_4	0.200	8622	9100	- 5.25
	0.250	9779	9212	+ 6.16
	0.400	12758	12041	+ 5.95
	0.500	14511	14443	+ 0.47
	0.600	16088	16450	- 2.20
GSP/I/d_{p_2}/h_{s_1}/R_1	0.200	5851	6922	-15.47
	0.400	8680	7975	+ 8.84
	0.500	9881	8600	+14.90
	0.700	11935	11515	+ 3.65
	0.833	13214	13555	- 2.52
GSP/I/d_{p_2}/h_{s_1}/R_2	0.200	6975	7389	- 5.60
	0.400	10308	9015	+14.34
	0.500	11703	10364	+12.92
	0.650	13601	13654	- 0.39
	0.750	14764	15660	- 5.72
GSP/I/d_{p_2}/h_{s_1}/R_3	0.166	7208	8212	-12.23
	0.250	9106	9317	- 2.26
	0.400	11896	11186	+ 6.35
	0.500	13524	14147	- 4.40
	0.650	15694	15891	- 1.24
GSP/I/d_{p_2}/h_{s_1}/R_4	0.166	8138	8883	- 8.39
	0.333	12129	11186	+ 8.43
	0.450	14376	13028	+10.35
	0.500	15268	14673	+ 4.06
	0.600	16934	16615	+ 1.92

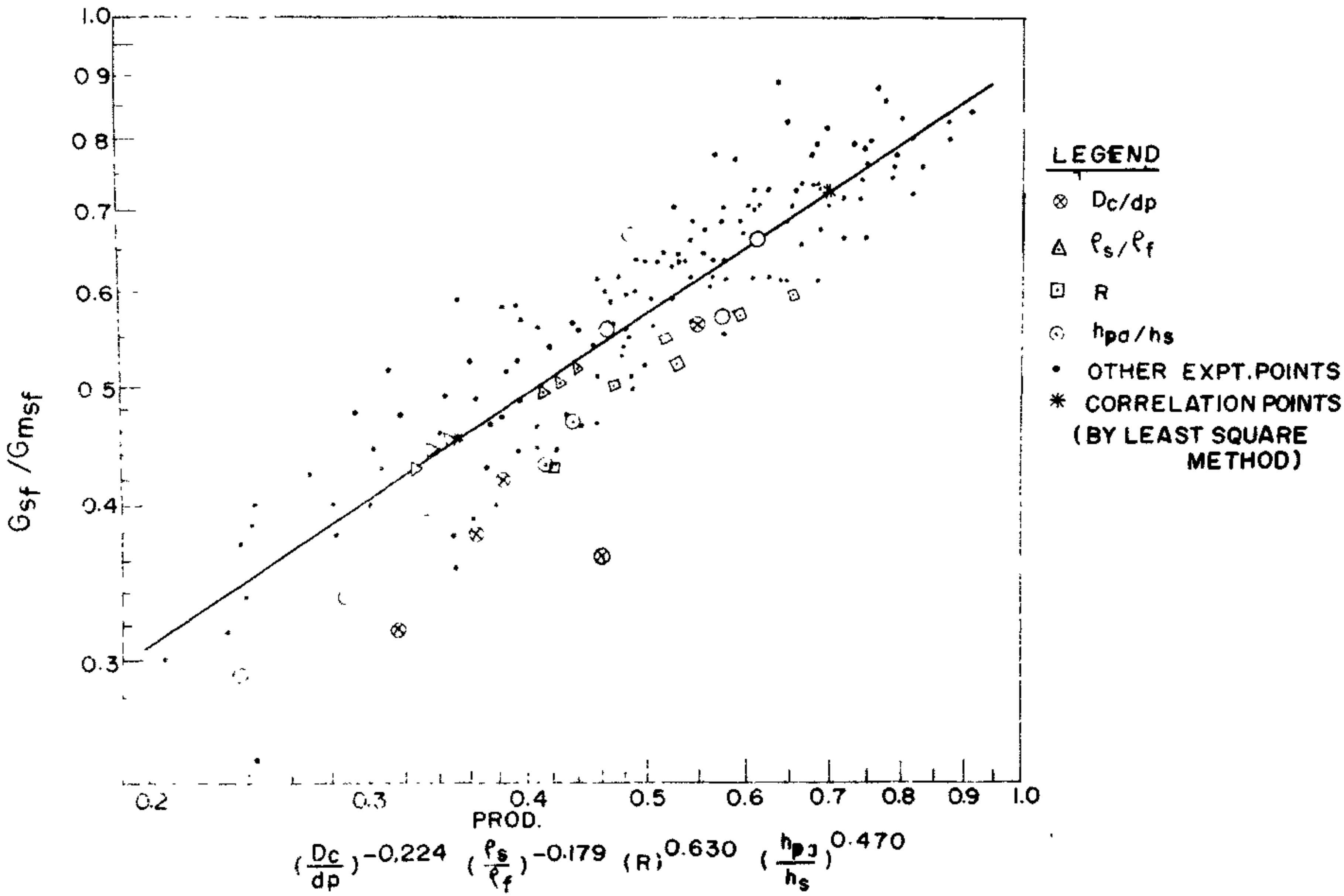


FIG. 6 A_1 RELATION OF G_{sf}/G_{msf} WITH SYSTEM VARIABLES.

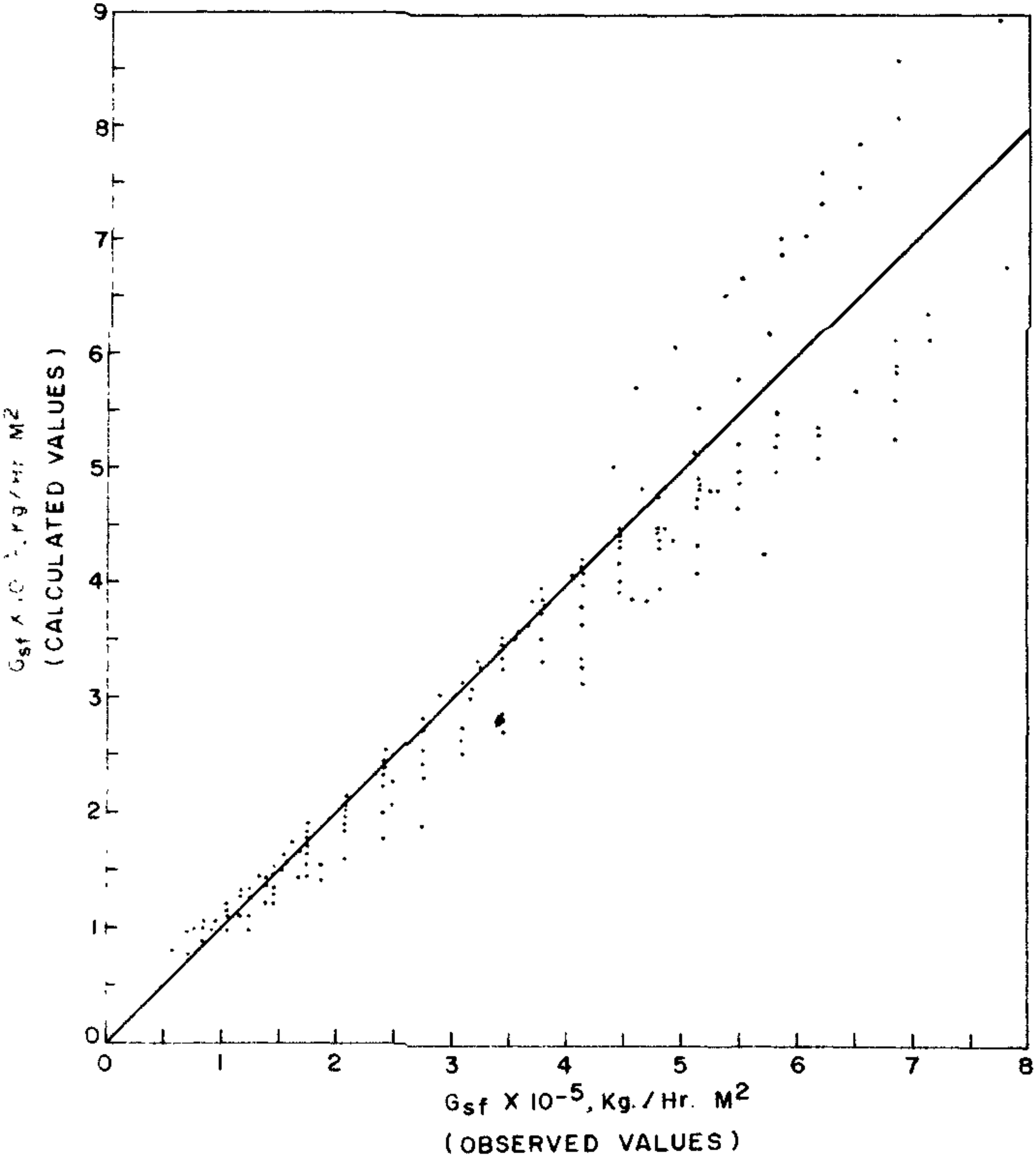
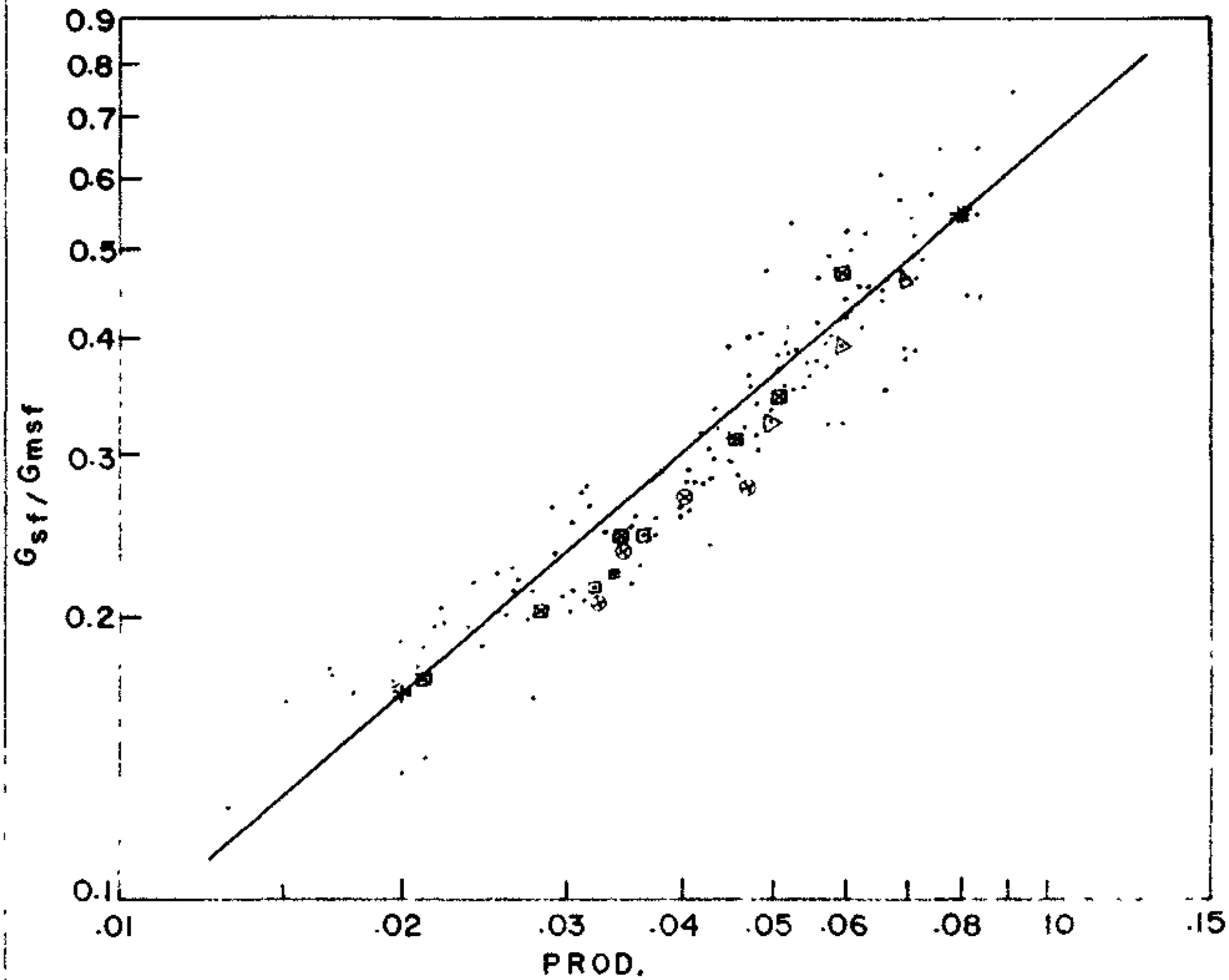


FIG 6 A_2 COMPARISON OF SEMI-FLUIDIZATION VELOCITIES.



$$\left(\frac{D_c}{d_p}\right)^{-0.206}\left(\frac{\rho_s}{\rho_f}\right)^{-0.372}(R)^{0.972}\left(\frac{h_{pa}}{h_s}\right)^{0.714}$$

LEGEND

⊗ D_c / d_p

⊡ ρ_s / ρ_f

△ R

⊠ h_{pa} / h_s

• OTHER EXPT POINTS

* CORRELATION POINTS (BY LEAST SQUARE METHOD)

FIG 6 B_1 RELATION OF G_{sf}/G_{msf} WITH SYSTEM VARIABLES.

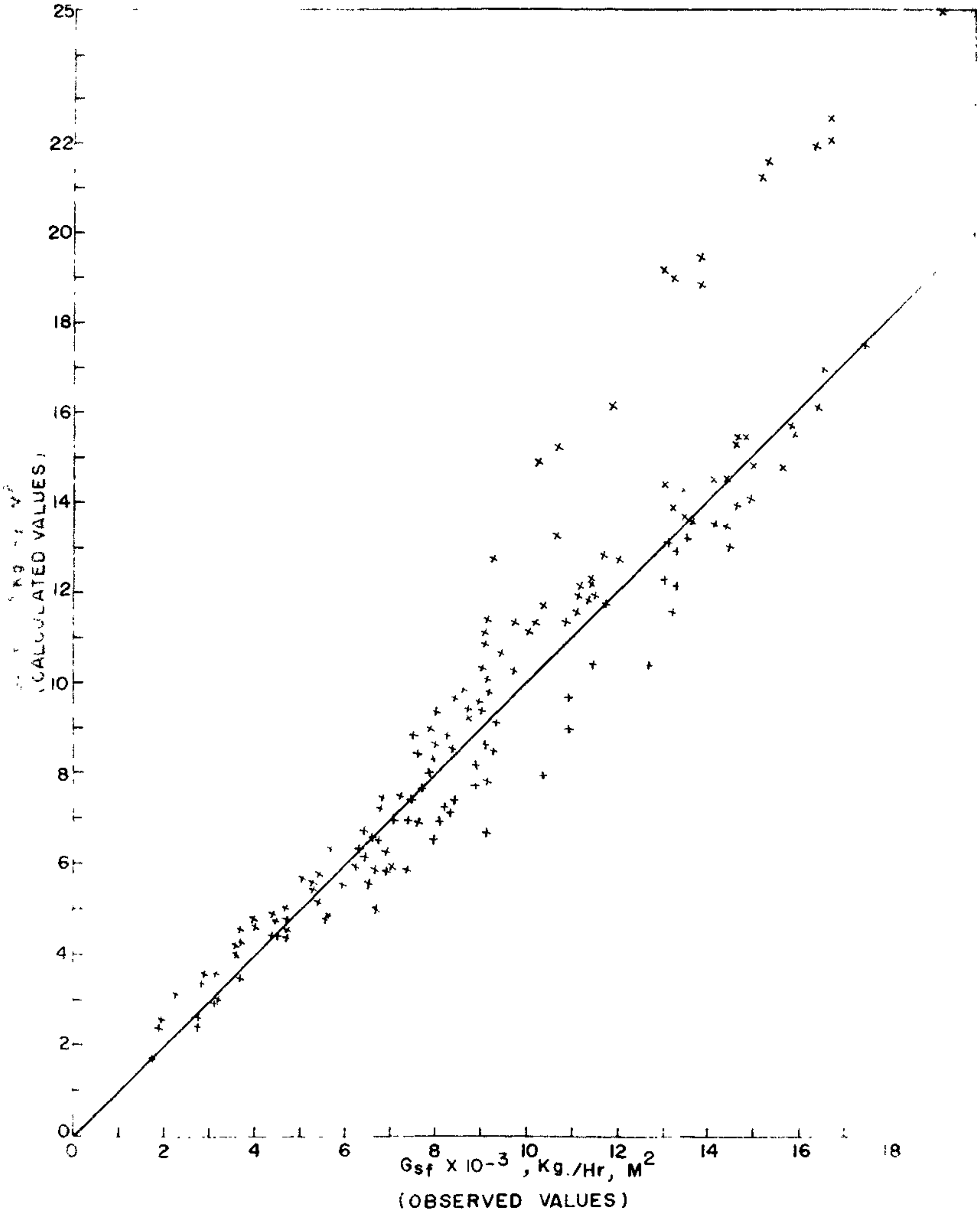


FIG 6 B_2 COMPARISON OF SEMI-FLUIDIZATION VELOCITIES

C H A P T E R - VII

PREDICTION OF PRESSURE DROP IN A SEMIFLUIDIZED BED

** The tables and figures referred in the text have been given at the end of the chapter .

PREDICTION OF PRESSURE DROP IN A SEMIFLUIDIZED BED

The pressure drop in a semifluidized bed should ideally, be equal to the algebraic sum of the pressure drop across the fluidized section and the packed section, since they are aligned in series in the direction of flow. While there is only one generalized equation namely,

$$\left(\frac{\Delta P}{L}\right)_f = (\rho_s - \rho_f)\ (1 - \epsilon_f) \qquad \ldots \qquad (7.1)$$

for the prediction of pressure drop across the fluidized bed, there are several correlations for the determination of packed bed pressure drop. A few important ones amongst them are the Kozney- Carman equation, Ergun's equation and the equation of Leva and co-workers.[1] In the present study, Ergun's equation has been used for the calculation of packed bed pressure drop.

As has been reported earlier[2] and observed in the present case, the porosity of the packed section presents difficulty for the calculation of overall pressure drop in the semi-fluidized bed. Available equations for packed bed pressure drops are quite sensitive to bed porosity variation. Also there are no direct ways of measuring the porosities of the fixed and the fluidized sections of the semifluidized bed simultaneously. This results in wide variation between the experimental and calculated values of pressure drops in a semifluidized bed. In an earlier communication, Roy and Sen Gupta[3] suggested a correction factor in terms of system variables, which can be used for the prediction of pressure drop in a gas-solid semifluidized bed. Here an attempt has been made to report the semifluidized bed pressure drop as a dimensionless ratio and relate it to various system variables.

Correlation :

A relation between the group, $\Delta P_T/\Delta P_{osf}$, and the other parameters can be written as follows -

$$\frac{\Delta P_T}{\Delta P_{osf}} = \phi\left[\frac{D_c}{d_p}, \frac{\rho_s}{\rho_f}, R, \frac{h_s}{D_c}, \frac{h_{pa}}{h_s}\right] \quad \ldots \quad (7.2)$$

During investigations it has been observed that, the height of the initial static bed has no appreciable effect on the semi-fluidized bed pressure drop and also on the onset of semifluidization velocity. In a semifluidized bed, the major contribution to pressure drop is due to the formation of packed bed below the top restraint and is independant of the total amount of material being distributed in the two sections. Since the column diameter has not been altered for a particular system. The effect of h_s/D_c is, not accounted for. Consequently the above equation reduces to,

$$\frac{\Delta P_T}{\Delta P_{osf}} = A \left(\frac{D_c}{d_p}\right)^{a_1} \left(\frac{\rho_s}{\rho_f}\right)^{a_2} (R)^{a_3} \left(\frac{h_{pa}}{h_s}\right)^{a_4} \quad \ldots \quad (7.3)$$

where, A is a constant and a_1, a_2, a_3 and a_4 are exponents of the system variables.

The effect of the individual parameters can be seen from tables $7.A_1$ and $7.B_1$. By plotting the pressure drop ratio against each of the system variables on log- log coordinates, the exponents of equation (7.3) are evaluated.

After substitution of these exponents, equation (7.3) becomes,

$$\frac{\Delta P_T}{\Delta P_{osf}} = A \left[\left(\frac{D_c}{d_p}\right)^{-0.218} \left(\frac{\rho_s}{\rho_f}\right)^{0.610} (R)^{0.354} \left(\frac{h_{pa}}{h_s}\right)^{1.130} \right]^{B} \quad \ldots \quad (7.4)$$

where, A is the coefficient and B is the exponent of the overall product.

The products have been calculated and presented in tables-7.A_2 and 7.B_2. In fig. 7.A_1 the pressure drop ratio has been plotted on log- log coordinates against the product $\left[\left(\frac{D_c}{d_p}\right)^{-0.218} \left(\frac{\rho_s}{\rho_f}\right)^{0.610} (R)^{0.354} \left(\frac{h_{pa}}{h_s}\right)^{1.130} \right]$. The data can be fitted well into a straight line by the least square method and the equation for this is given by

$$\frac{\Delta P_T}{\Delta P_{osf}} = 19.50 \left(\frac{D_c}{d_p}\right)^{-0.17} \left(\frac{\rho_s}{\rho_f}\right)^{0.48} (R)^{0.28} \left(\frac{h_{pa}}{h_s}\right)^{0.89} \quad \ldots \quad (7.5A)$$

By a similar approach the exponents have been evaluated for the gas- solid system and the product of the system variables has been plotted against the pressure drop ratio (fig.7.B_1). The data fits well into a straight line relation and the equation for this is given by

$$\frac{\Delta P_T}{\Delta P_{osf}} = 0.22 \left(\frac{D_c}{d_p}\right)^{-0.21} \left(\frac{\rho_s}{\rho_f}\right)^{0.43} (R)^{1.71} \left(\frac{h_{pa}}{h_s}\right)^{1.24} \quad \ldots \quad (7.5B)$$

The values of the pressure drop calculated by using the above equations have been compared with the experimental values in tables-7.A_3 and 7.B_3.

Though it can be said that in general there is no appreciable deviation of the calculated values from the experimental, there are some deviations to large extent in the case of particles of larger size , higher density and in the regions of packed bed height approaching that of initial static bed height. In some cases the experimental values are high while in others the calculated values are higher.

These type of discrepancies have been observed by earlier workers (Raja Rao et-el). The reasons may be due to the following:-

(i) The configuration of screen

(ii) The orientation of the particles to the screen opening when they approach the screen

(iii) The blinding of screen

(iv) Influence of particle shape

A better explanation can not be given at this stage unless more detailed studies are attempted in this aspect.

References

1. Leva,M.,'Fluidization', Mc Graw Hill Book Co., Inc., New York (1959).

2. Fan, L.T. and Wen., C.Y., A.I.Ch.E.Jl.,7, 606 (1961)

3. Roy, G.K. and Sen Gupta, P., The Chem.Engg. Jl., 5, 191, (1973).

Nomenclature

D_c = Diameter of the column (semifluidizer), L

d_p = Particle diameter, L

h_{pa} = Height of packed section in semi-fluidization, L

h_s = Height of initial static bed, L

$\left(\frac{\Delta P}{L}\right)_f$ = Pressure gradient across fluidized bed, FL^{-3}

ΔP_{osf} = Pressure drop across bed corresponding to the onset of semi-fluidization condition, FL^{-2}

ΔP_T = Overall pressure drop across the semifluidized bed, FL^{-2}

R = Bed expansion ratio in semi-fluidization dimensionless.

ρ_s = Density of solid, ML^{-3}

ρ_f = Density of fluid, ML^{-3}

Φ = Function

ϵ_f = Porosity of fluidized bed, dimensionless

TABLE- 7.A_1

Effect of various system parameters on the pressure drop ($\Delta P_T / \Delta P_{osf}$) ratio.

(a) Influence of wall effect :-

Sl. No.	Operating parameter, D_c/d_p	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters.
1.	10.42	60.4	734.0	12.15	$\rho_s/\rho_f = 2.83$
2.	23.00	73.6	639.0	8.68	$R = 2.00$
3.	46.15	74.7	630.0	8.43	$h_s/D_c = 2.36$
4.	65.50	85.6	694.0	8.11	$h_{pa}/h_s = 0.500$
5.	93.00	80.2	620.0	7.73	

(b) Influence of density ratio:-

Sl. No.	Operating parameter, ρ_s/ρ_f	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters.
1.	2.83	73.6	639.0	8.68	$D_c/d_p = 23.00$
2.	3.72	81.6	870.0	10.66	$R = 2.00$
3.	4.45	123.4	1680.0	13.61	$h_s/D_c = 2.36$
4.	5.25	143.8	1605.0	11.16	$h_{pa}/h_s = 0.500$

(c) Influence of bed expansion ratio :-

Sl. No.	Operating parameter, R	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters
1.	2.00	73.6	639.0	8.68	$D_c/d_p = 23.00$
2.	2.50	80.4	670.0	8.33	$\rho_s/\rho_f = 2.83$
3.	3.00	77.1	720.0	9.34	$h_s/D_c = 2.360$
4.	3.50	82.2	830.0	10.10	$h_pa/h_s = 0.500$

Contd...

T A B L E- 7.A_1 (contd.)

(d) Effect of packed bed formation :-

Sl. No.	Operating parameter, h_{pa}/h_s	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters.
1.	0.250	73.6	326.0	4.44	
2.	0.400		435.0	5.91	D_c/d_p = 23.00
3.	0.500		639.0	8.68	ρ_s/ρ_f = 2.83
4.	0.666		775.0	10.53	R = 2.00
5.	0.800		1033.0	14.04	h_s/D_c = 2.36
6.	0.917		1360.0	18.48	

T A B L E - 7.B_1

Effect of various system parameters on the pressure drop ratio.

(a) Influence of wall effect :-

Sl. No.	Operating parameter, D_c/d_p	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters
1.	18.1	152.7	565.0	3.70	$\varrho_s/\varrho_f = 1210.0$
2.	39.8	173.1	475.0	2.74	$R = 2.0$
3.	80.0	176.5	402.0	2.28	$h_s/D_c = 1.363$
4.	113.3	168.0	385.0	2.29	$h_{pa}/h_s = 0.500$

(b) Influence of density ratio :-

Sl. No.	Operating parameter, ϱ_s/ϱ_f	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters
1.	1210.0	173.1	475.0	2.74	$D_c/d_p = 39.8$
2.	1590.0	171.8	613.0	3.57	$R = 2.0$
3.	1900.0	221.5	782.0	3.53	$h_s/D_c = 1.363$
4.	2244.0	286.5	980.4	3.42	$h_{pa}/h_s = 0.500$

(c) Influence of bed expansion ratio :-

Sl. No.	Operating parameter, R	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters
1.	2.0	173.1	475.0	2.74	$D_c/d_p = 39.8$
2.	2.5	205.3	764.0	3.72	$\varrho_s/\varrho_f = 1210.0$
3.	3.0	220.4	1220.0	5.54	$h_s/D_c = 1.363$
4.	3.5	231.6	2245.0	9.69	$h_{pa}/h_s = 0.500$

Contd..

TABLE- 7.B_1 (Contd.)

(d) Effect of packed bed formation :-

Sl. No.	Operating parameter $\frac{h_{pa}}{h_s}$	ΔP_{osf} Kg./M^2	ΔP_T Kg./M^2	$\frac{\Delta P_T}{\Delta P_{osf}}$	Constant parameters
1.	0.200	173.1	155.0	0.90	
2.	0.300		236.5	1.37	
3.	0.400		387.0	2.24	D_c/d_p = 39.8
4.	0.500		475.0	2.74	ρ_s/ρ_f = 1210.0
5.	0.600		813.0	4.70	h_s/D_c = 1.363
6.	0.700		971.0	5.61	R = 2.0
7.	0.866		1610.0	9.30	

TABLE- 7.A2

Relation of pressure drop ratio ($\Delta P_T / \Delta P_{osf}$) with system variables.

Sl. No.	$\frac{D_c}{d_p}$	ρ_s / ρ_f	R	$\frac{h_{pa}}{h_s}$	Prod.	ΔP_{osf} $\frac{Kg.}{M^2}$	ΔP_T $\frac{Kg.}{M^2}$	$\frac{\Delta P_T}{\Delta P_{osf}}$
1	2	3	4	5	6	7	8	9
1.	10.42	2.83	2.0	0.500	0.661	60.4	734.0	12.15
2.	23.00	2.83	2.0	0.500	0.557	73.6	639.0	8.68
3.	46.15	2.83	2.0	0.500	0.478	74.7	630.0	8.43
4.	65.50	2.83	2.0	0.500	0.442	85.6	694.0	8.11
5.	93.00	2.83	2.0	0.500	0.410	80.2	620.0	7.73
6.	23.00	3.72	2.0	0.500	0.658	81.6	870.0	10.66
7.	23.00	4.45	2.0	0.500	0.733	123.4	1680.0	13.61
8.	23.00	5.25	2.0	0.500	0.811	143.8	1605.0	11.16
9.	23.00	2.83	2.5	0.500	0.602	80.4	670.0	8.33
10.	23.00	2.83	3.0	0.500	0.642	77.1	720.0	9.34
11.	23.00	2.83	3.5	0.500	0.678	82.2	830.0	10.10
12.	23.00	2.83	2.0	0.250	0.254	73.6	326.0	4.44
13.	23.00	2.83	2.0	0.400	0.432	73.6	435.0	5.91
14.	23.00	2.83	2.0	0.666	0.770	73.6	775.0	10.53
15.	23.00	2.83	2.0	0.800	0.947	73.6	1033.0	14.04
16.	23.00	2.83	2.0	0.917	1.104	73.6	1360.0	18.48

Contd...

T A B L E- 7.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
17.	10.42	2.83	2.0	0.333	0.418	60.4	571.0	9.45
18.				0.600	0.812		870.0	14.40
19.				0.750	1.045		1116.0	18.48
20.				0.883	1.257		1400.0	23.18
21.			2.5	0.333	0.452	64.8	734.0	11.33
22.				0.600	0.879		939.0	14.49
23.				0.700	1.046		1101.0	16.99
24.				0.800	1.217		1320.0	20.37
25.				0.850	1.303		1495.0	23.07
26.			3.0	0.300	0.428	71.5	761.0	10.64
27.				0.550	0.850		965.0	13.50
28.				0.700	1.116		1238.0	17.31
29.				0.850	1.390		1630.0	22.80
30.			3.5	0.300	0.452	78.0	816.0	10.46
31.				0.450	0.716		965.0	12.37
32.				0.633	1.051		1238.0	15.87
33.				0.833	1.435		1522.0	19.51
34.				0.950	1.665		2244.0	28.77
35.	23.00	2.83	2.5	0.150	0.154	80.4	389.5	4.84
36.				0.266	0.295		408.0	5.07
37.				0.416	0.489		611.0	7.60
38.				0.600	0.740		789.0	9.81
39.				0.750	0.952		1170.0	14.55
40.				0.900	1.170		1713.0	21.31

Contd...

T A B L E- $7.A_2$ (Contd.)

1	2	3	4	5	6	7	8	9
41.	23.00	2.83	3.0	0.284	0.339	77.1	449.0	5.82
42.				0.416	0.522		625.0	8.11
43.				0.600	0.789		925.0	12.00
44.				0.750	1.015		1170.0	15.18
45.				0.917	1.275		1793.0	23.26
46.			3.5	0.333	0.227	82.2	666.0	8.10
47.				0.550	0.400		993.0	12.08
48.				0.666	0.489		1280.0	15.57
49.				0.800	0.612		1630.0	19.83
50.				0.917	0.714		2215.0	26.95
51.	46.15	2.83	2.0	0.125	0.053	74.7	350.5	4.69
52.				0.416	0.206		476.0	6.37
53.				0.583	0.302		761.0	10.19
54.				0.750	0.401		1373.6	18.39
55.				0.866	0.472		2067.0	27.67
56.			2.5	0.125	0.108	78.0	391.2	5.02
57.				0.400	0.402		680.0	8.72
58.				0.600	0.636		910.0	11.67
59.				0.800	0.881		1400.0	17.95
60.				0.917	1.027		1850.0	23.72
61.			3.0	0.166	0.159	82.7	490.0	5.93
62.				0.466	0.510		707.0	8.55
63.				0.733	0.850		1238.0	14.97
64.				0.850	1.005		1700.0	20.56
65.				0.933	1.117		2148.0	25.97

Contd....

TABLE- 7.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
66.	46.15	2.83	3.5	0.125	0.121	80.7	504.0	6.25
67.				0.375	0.421		734.0	9.10
68.				0.633	0.760		1115.0	13.82
69.				0.800	0.992		1645.0	20.38
70.				0.883	1.109		2067.0	25.61
71.				0.966	1.227		2570.0	31.85
72.	65.50	2.83	2.0	0.200	0.157	85.6	300.0	3.50
73.				0.300	0.248		557.0	6.51
74.				0.733	0.681		1182.0	13.81
75.				0.833	0.787		1630.0	19.04
76.				0.917	0.877		2300.0	26.87
77.			2.5	0.150	0.123	89.5	217.5	2.43
78.				0.400	0.372		544.0	6.08
79.				0.600	0.588		911.0	10.18
80.				0.750	0.756		1470.0	16.42
81.				0.950	0.988		2720.0	30.39
82.			3.0	0.166	0.147	96.5	326.0	3.38
83.				0.416	0.414		694.0	7.19
84.				0.666	0.706		1305.0	13.52
85.				0.833	0.909		2000.0	20.73
86.				0.950	1.054		3370.0	34.92
87.			3.5	0.100	0.087	96.8	218.5	2.26
88.				0.250	0.246		408.0	4.21
89.				0.550	0.600		1088.0	11.24
90.				0.750	0.851		1810.0	18.70
91.				0.866	1.002		2485.0	25.67

Contd...

T A B L E- 7.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
92.	93.00	2.83	2.0	0.250	0.187	80.2	299.5	3.73
93.				0.450	0.365		530.0	6.61
94.				0.600	0.504		856.0	10.67
95.				0.750	0.649		1388.0	17.31
96.				0.950	0.847		2230.0	27.81
97.			2.5	0.166	0.128	80.7	272.0	3.37
98.				0.400	0.345		585.0	7.25
99.				0.666	0.615		1210.0	14.99
100.				0.800	0.756		1835.0	22.74
101.				0.917	0.882		2380.0	29.49
102.			3.0	0.200	0.168	84.7	475.0	5.61
103.				0.500	0.474		1115.0	13.16
104.				0.666	0.655		1537.0	18.15
105.				0.800	0.806		2160.0	25.50
106.				0.950	0.979		3280.0	38.72
107.			3.5	0.292	0.272	84.6	665.5	7.87
108.				0.550	0.557		1264.0	14.94
109.				0.750	0.791		1985.0	23.46
110.				0.850	0.911		2445.0	28.90
111.				0.950	1.033		3620.0	42.79

Contd...

TABLE- 7.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
112.	23.00	3.72	2.0	0.300	0.369	81.6	516.5	6.33
113.				0.400	0.511		707.0	8.66
114.				0.600	0.808		1075.0	13.17
115.				0.733	1.013		1291.0	15.82
116.				0.950	1.358		1930.0	23.65
117.			2.5	0.166	0.205	83.2	599.0	7.20
118.				0.333	0.450		844.0	10.14
119.				0.500	0.712		1089.0	13.09
120.				0.666	0.984		1373.0	16.50
121.				0.900	1.383		2015.0	24.22
122.			3.0	0.250	0.346	83.2	748.0	8.99
123.				0.333	0.479		884.0	10.63
124.				0.500	0.759		1182.0	14.21
125.				0.666	1.049		1481.0	17.80
126.				0.900	1.475		2242.0	26.95
127.			3.5	0.150	0.206	85.7	640.0	7.47
128.				0.300	0.450		980.0	11.44
129.				0.450	0.712		1280.0	14.94
130.				0.600	0.985		1550.0	18.09
131.				0.850	1.460		2284.0	26.65

Contd...

T A B L E- 7.A_2 (Contd.)

1	2	3	4	5	6	7	8	9
132.	23.00	4.45	2.0	0.150	0.188	123.4	775.0	6.28
133.				0.250	0.335		980.0	7.94
134.				0.400	0.569		1388.0	11.25
135.				0.533	0.788		1754.0	14.21
136.				0.650	0.985		2490.0	20.18
137.				0.850	1.335		3904.0	31.64
138.			2.5	0.200	0.281	130.4	1061.0	8.14
139.				0.300	0.445		1482.0	11.37
140.				0.400	0.616		1920.0	14.72
141.				0.500	0.793		2406.0	18.45
142.				0.650	1.067		2952.0	22.64
143.				0.800	1.349		4060.0	31.13
144.			3.0	0.150	0.217	134.1	899.0	6.70
145.				0.250	0.386		1482.0	11.05
146.				0.350	0.565		1890.0	14.09
147.				0.457	0.781		2395.0	17.86
148.				0.550	0.942		2910.0	21.70
149.				0.666	1.169		3430.0	25.58
150.				0.833	1.506		4700.0	35.05
151.			3.5	0.200	0.317	137.7	1430.0	10.38
152.				0.300	0.501		1810.0	13.14
153.				0.400	0.694		2355.0	17.10
154.				0.600	1.098		3295.0	23.93
155.				0.850	1.627		5110.0	37.11

Contd...

T A B L E- 7.A2 (Contd.)

1	2	3	4	5	6	7	8	9
156.	23.00	5.25	2.0	0.200	0.288	143.8	666.0	4.63
157.				0.333	0.512		980.0	6.82
158.				0.650	1.091		1985.0	13.80
159.				0.750	1.282		2500.0	17.39
160.				0.833	1.444		3505.0	24.37
161.			2.5	0.250	0.401	159.4	727.0	4.56
162.				0.333	0.555		980.0	6.15
163.				0.416	0.713		1278.0	8.02
164.				0.633	1.146		1985.0	12.45
165.				0.750	1.388		2650.0	16.62
166.			3.0	0.217	0.365	162.2	830.0	5.12
167.				0.400	0.727		1182.0	7.29
168.				0.500	0.936		1550.0	9.56
169.				0.666	1.295		2300.0	14.18
170.				0.850	1.705		3460.0	21.33
171.			3.5	0.200	0.351	162.4	925.0	5.70
172.				0.350	0.661		1332.0	8.20
173.				0.550	1.101		2015.0	12.41
174.				0.700	1.446		2870.0	17.67
175.				0.850	1.801		4180.0	25.74

T A B L E- 7.B2

Relation of pressure drop ratio ($\Delta P_T / \Delta P_{osf}$) with system variables.

Sl. No.	$\frac{D_c}{d_p}$	ρ_s / ρ_f	R	$\frac{h_{pa}}{h_s}$	Prod.	ΔP_{osf} (Kg./M²)	ΔP_T (Kg./M²)	$\frac{\Delta P_T}{\Delta P_{osf}}$
1	2	3	4	5	6	7	9	9
1.	18.10	1210.0	2.0	0.500	33.63	152.7	565.0	3.70
2.	39.80	1210.0	2.0	0.500	27.27	173.1	475.0	2.74
3.	80.00	1210.0	2.0	0.500	22.56	176.5	402.0	2.28
4.	113.30	1210.0	2.0	0.500	20.62	168.0	385.0	2.29
5.	39.80	1590.0	2.0	0.500	31.47	171.8	613.0	3.57
6.	39.80	1900.0	2.0	0.500	34.84	221.5	782.0	3.53
7.	39.80	2244.0	2.0	0.500	38.22	286.5	980.4	3.42
8.	39.80	1210.0	2.5	0.500	44.14	205.3	764.0	3.72
9.	39.80	1210.0	3.0	0.500	65.32	220.4	1220.0	5.54
10.	39.80	1210.0	3.5	0.500	91.32	231.6	2245.0	9.69
11.	39.80	1210.0	2.0	0.200	6.48	173.1	155.0	0.90
12.	39.80	1210.0	2.0	0.300	12.24	173.1	236.5	1.37
13.	39.80	1210.0	2.0	0.400	19.21	173.1	387.0	2.24
14.	39.80	1210.0	2.0	0.600	36.32	173.1	813.0	4.70
15.	39.80	1210.0	2.0	0.700	46.32	173.1	971.0	5.61
16.	39.80	1210.0	2.0	0.866	64.67	173.1	1610.0	9.30

Contd...

T A B L E-7.B2 (Contd.)

1	2	3	4	5	6	7	8	9
17.	18.10	1210.0	2.0	0.166	5.97	152.7	244.0	1.60
18.				0.333	17.79		371.0	2.43
19.				0.666	52.79		809.0	5.30
20.				0.833	75.00		1352.0	8.85
21.			2.5	0.200	12.94	178.1	339.0	1.90
22.				0.333	28.79		565.0	3.17
23.				0.500	54.43		1032.0	5.79
24.				0.600	72.50		1523.0	8.55
25.				0.666	85.44		1944.0	10.92
26.			3.0	0.150	12.16	200.0	416.0	2.08
27.				0.250	27.19		475.0	2.38
28.				0.400	56.73		753.0	3.77
29.				0.500	80.55		1215.0	6.08
30.				0.650	121.70		2178.0	10.90
31.			3.5	0.166	19.98	213.8	665.0	3.11
32.				0.300	50.53		1128.0	5.28
33.				0.400	79.31		1990.0	9.31
34.				0.500	112.61		3205.0	15.00
35.	39.80	1210.0	2.5	0.133	5.51	205.3	186.0	0.91
36.				0.200	10.49		303.0	1.48
37.				0.333	23.35		486.0	2.37
38.				0.650	66.68		1375.0	6.70
39.				0.833	98.42		2200.0	10.71

Contd..

TABLE- 7.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
40.	39.80	1210.0	3.0	0.200	15.53	220.4	428.0	1.94
41.				0.333	34.55		605.0	2.75
42.				0.666	102.53		2095.0	9.51
43.				0.766	127.73		2780.0	12.61
44.			3.5	0.200	21.71	231.6	660.0	2.85
45.				0.333	48.30		1428.0	6.17
46.				0.666	143.33		3210.0	13.86
47.	80.00	1210.0	2.0	0.150	3.41	176.5	137.0	0.78
48.				0.300	10.12		215.5	1.22
49.				0.650	34.08		787.0	4.46
50.				0.800	47.20		1208.0	6.84
51.				0.900	56.80		1896.0	10.74
52.			2.5	0.166	6.48	199.4	141.0	0.71
53.				0.333	19.31		255.0	1.28
54.				0.500	36.50		532.0	2.67
55.				0.650	55.15		1060.0	5.32
56.				0.750	69.03		1743.0	8.74
57.				0.900	91.92		2780.0	13.94
58.			3.0	0.166	9.59	218.9	170.6	0.78
59.				0.250	18.24		265.0	1.21
60.				0.400	38.05		509.0	2.33
61.				0.500	54.02		789.0	3.60
62.				0.666	84.80		1670.0	7.63
63.				0.866	128.12		2815.0	12.86

Contd.

T A B L E- 7.B$_2$ (Contd.)

1	2	3	4	5	6	7	8	9
64.	80.00	1210.0	3.5	0.200	17.96	237.5	254.5	1.07
65.				0.333	39.95		606.0	2.55
66.				0.500	75.52		853.0	3.59
67.				0.633	109.52		1590.0	6.70
68.				0.800	158.05		2545.0	10.72
69.				0.900	190.19		3545.0	14.93
70.	113.30	1210.0	2.0	0.250	6.96	168.0	168.0	1.00
71.				0.400	14.52		254.0	1.51
72.				0.666	32.36		617.5	3.68
73.				0.750	38.99		982.0	5.85
74.				0.850	47.47		1220.0	7.26
75.				0.900	51.92		1813.0	10.79
76.			2.5	0.100	2.68	205.3	124.1	0.60
77.				0.200	7.93		173.5	0.85
78.				0.333	17.65		313.5	1.53
79.				0.500	33.37		559.0	2.72
80.				0.616	46.36		928.0	4.52
81.				0.700	56.67		1006.0	4.90
82.				0.800	69.83		1663.0	8.10
83.				0.883	81.56		2390.0	11.64
84.			3.0	0.166	8.76	218.9	153.0	0.70
85.				0.350	28.21		372.5	1.70
86.				0.500	49.38		672.0	3.07
87.				0.600	65.78		1138.0	5.20
88.				0.700	83.87		1787.0	8.16
89.				0.833	110.12		2370.0	10.83

TABLE- 7.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
90.	113.30	1210.0	3.5	0.166	12.25	237.5	368.5	1.55
91.				0.333	36.52		616.0	2.59
92.				0.500	69.04		1028.0	4.33
93.				0.600	91.95		1700.0	7.15
94.				0.750	130.56		2613.0	11.00
95.	39.80	1590.0	2.0	0.166	5.59	171.8	200.5	1.17
96.				0.300	14.13		310.0	1.80
97.				0.750	59.55		914.0	5.32
98.				0.850	72.50		1645.0	9.58
99.			2.5	0.200	12.12	181.2	245.5	1.36
100.				0.250	17.20		306.5	1.69
101.				0.417	38.39		510.0	2.82
102.				0.500	50.96		623.0	3.44
103.				0.600	67.88		969.0	5.35
104.				0.800	106.64		2033.0	11.22
105.			3.0	0.183	15.58	204.1	306.5	1.50
106.				0.250	25.46		385.0	1.89
107.				0.400	53.12		564.0	2.76
108.				0.500	75.42		941.0	4.61
109.				0.666	118.38		1800.0	8.82
110.				0.750	142.64		2605.0	12.76

Contd...

TABLE- 7.B2 (Contd.)

1	2	3	4	5	6	7	8	9
111.	39.80	1590.0	3.5	0.166	18.71	218.6	420.0	1.92
112.				0.250	35.59		508.0	2.32
113.				0.400	74.26		790.0	3.61
114.				0.500	105.43		1343.0	6.14
115.				0.600	140.43		1960.0	8.97
116.				0.750	199.40		3620.0	16.56
117.	39.80	1900.0	2.0	0.200	8.29	221.5	347.0	1.57
118.				0.250	11.77		438.0	1.98
119.				0.450	29.58		711.0	3.21
120.				0.700	59.21		1417.0	6.40
121.				0.800	72.96		2445.0	11.04
122.			2.5	0.250	19.05	260.2	694.0	2.67
123.				0.400	39.74		1023.0	3.93
124.				0.500	56.42		1443.0	5.55
125.				0.650	85.24		1605.0	6.17
126.				0.750	106.70		2560.0	9.84
127.			3.0	0.200	19.85	288.2	455.0	1.58
128.				0.300	37.47		787.0	2.73
129.				0.400	58.81		1240.0	4.30
130.				0.500	83.50		1825.0	6.34
131.				0.600	111.22		2450.0	8.50
132.				0.700	141.81		3415.0	11.85

Contd...

T A B L E- 7.B_2 (Contd.)

1	2	3	4	5	6	7	8	9
133.	39.80	1900.0	3.5	0.200	27.75	313.8	700.0	2.23
134.				0.250	39.41		926.0	2.95
135.				0.400	82.21		1599.0	5.10
136.				0.500	116.73		2875.0	9.16
137.				0.600	155.48		4225.0	13.46
138.	39.80	2244.0	2.0	0.200	9.09	286.5	188.2	0.66
139.				0.400	26.93		581.0	2.03
140.				0.700	64.94		1381.0	4.82
141.				0.833	85.27		2070.0	7.23
142.			2.5	0.200	14.71	326.7	225.0	0.69
143.				0.400	43.58		599.0	1.83
144.				0.500	61.88		997.6	3.05
145.				0.650	93.49		1180.0	3.61
146.				0.750	117.03		1821.0	5.57
147.			3.0	0.166	16.25	344.8	240.0	0.70
148.				0.250	30.92		464.0	1.35
149.				0.400	64.50		843.4	2.45
150.				0.500	91.58		1476.0	4.28
151.				0.650	138.36		2082.0	6.04
152.			3.5	0.166	22.71	374.5	323.0	0.86
153.				0.333	67.72		775.4	2.07
154.				0.450	108.62		1304.0	3.48
155.				0.500	128.03		1683.0	4.49
156.				0.600	170.52		2006.0	5.36

TABLE- 7.A_3

Varification of the correlation

Run No.	$\frac{h_{pa}}{h_s}$	ΔP_T, Kg./M^2 Calculated	Experimental
1	2	3	4
$LSP/D/d_{p_1}/h_{s_1}/R_1$	0.333	595.9	571.0
	0.500	855.8	734.0
	0.600	1005.4	870.0
	0.750	1226.5	1116.0
	0.883	1418.5	1400.0
$LSP/D/d_{p_1}/h_{s_1}/R_2$	0.333	680.3	734.0
	0.600	1147.9	939.0
	0.700	1317.3	1101.0
	0.800	1483.7	1320.0
	0.850	1565.5	1495.0
$LSP/D/d_{p_1}/h_{s_1}/R_3$	0.300	719.6	761.0
	0.550	1234.7	965.0
	0.700	1529.9	1238.0
	0.850	1818.3	1630.0
$LSP/D/d_{p_1}/h_{s_1}/R_4$	0.300	819.6	816.0
	0.450	1176.6	965.0
	0.633	1594.2	1238.0
	0.833	2034.7	1522.0
	0.950	2287.0	2244.0

Contd...

TABLE- 7.A_3 (Contd.)

1	2	3	4
LSP/D/d_{p_2}/h_{s_1}/R_1	0.250	490.9	326.0
	0.400	744.7	435.0
	0.500	909.4	639.0
	0.666	1172.5	775.0
	0.800	1380.9	1033.0
	0.917	1559.1	1360.0
LSP/D/d_{p_2}/h_{s_1}/R_2	0.150	362.2	389.5
	0.266	602.3	408.0
	0.416	896.7	611.0
	0.500	1057.3	670.0
	0.600	1242.1	789.0
	0.750	1515.4	1170.0
	0.900	1782.6	1713.0
LSP/D/d_{p_2}/h_{s_1}/R_3	0.284	644.3	449.0
	0.416	905.2	625.0
	0.500	1067.2	720.0
	0.600	1253.8	925.0
	0.750	1529.7	1170.0
	0.917	1829.7	1793.0
LSP/D/d_{p_2}/h_{s_1}/R_4	0.333	827.2	666.0
	0.500	1188.0	830.0
	0.550	1292.5	993.0
	0.666	1531.6	1280.0
	0.800	1804.0	1630.0
	0.917	2036.8	2215.0

Contd..

T A B L E-7.A_3 (Contd.)

1	2	3	4
$LSP/D/d_{p_3}/h_{s_1}/R_1$	0.125	238.4	350.5
	0.416	695.5	476.0
	0.500	820.0	630.0
	0.583	940.0	761.0
	0.750	1175.3	1373.6
	0.866	1335.9	2067.0
$LSP/D/d_{p_3}/h_{s_1}/R_2$	0.125	264.9	391.2
	0.400	746.2	680.0
	0.600	1070.5	910.0
	0.800	1383.6	1400.0
	0.917	1562.2	1850.0
$LSP/D/d_{p_3}/h_{s_1}/R_3$	0.166	380.8	490.0
	0.466	953.9	707.0
	0.733	1428.2	1238.0
	0.850	1629.4	1700.0
	0.933	1770.4	2148.0
$LSP/D/d_{p_3}/h_{s_1}/R_4$	0.125	301.3	504.0
	0.375	802.0	734.0
	0.633	1277.9	1115.0
	0.800	1573.3	1645.0
	0.883	1717.5	2067.0
	0.966	1860.6	2570.0

Contd...

TABLE-7.A_3 (Contd.)

1	2	3	4
$LSP/D/d_{p_4}/h_{s_1}/R_1$	0.200	391.5	300.0
	0.300	562.0	557.0
	0.500	886.3	694.0
	0.733	1244.8	1182.0
	0.833	1395.1	1630.0
	0.917	1519.5	2300.0
$LSP/D/d_{p_4}/h_{s_1}/R_2$	0.150	337.9	217.5
	0.400	807.7	544.0
	0.600	1158.7	911.0
	0.750	1413.6	1470.0
	0.950	1744.9	2720.0
$LSP/D/d_{p_4}/h_{s_1}/R_3$	0.166	419.1	326.0
	0.416	949.4	694.0
	0.666	1443.1	1305.0
	0.833	1761.9	2000.0
	0.950	1980.4	3370.0
$LSP/D/d_{p_4}/h_{s_1}/R_4$	0.100	280.0	218.5
	0.250	632.8	408.0
	0.550	1275.4	1088.0
	0.750	1680.3	1810.0
	0.866	1910.0	2485.0

Contd...

T A B L E- 7.A_3 (Contd.)

1	2	3	4
LSP/D/d_{p_5}/h_{s_1}/R_1	0.250	422.3	299.5
	0.450	712.0	530.0
	0.500	782.4	620.0
	0.600	919.1	856.0
	0.750	1121.4	1388.0
	0.950	1384.1	2230.0
LSP/D/d_{p_5}/h_{s_1}/R_2	0.166	313.7	272.0
	0.400	686.0	585.0
	0.666	1080.1	1210.0
	0.800	1272.2	1835.0
	0.917	1436.4	2380.0
LSP/D/d_{p_5}/h_{s_1}/R_3	0.200	408.9	475.0
	0.500	925.6	1115.0
	0.666	1193.3	1537.0
	0.800	1405.5	2160.0
	0.950	1637.6	3280.0
LSP/D/d_{p_5}/h_{s_1}/R_4	0.292	597.0	665.5
	0.550	1050.2	1264.0
	0.750	1383.6	1985.0
	0.850	1546.7	2445.0
	0.950	1707.9	3620.0

Contd....

T A B L E- 7.A_3 (Contd.)

1	2	3	4
LSP/Cr./d_{p_2}/h_{s_1}/R_1	0.300	729.3	516.5
	0.400	941.9	707.0
	0.500	1150.2	870.0
	0.600	1351.3	1075.0
	0.733	1615.4	1291.0
	0.950	2035.0	1930.0
LSP/Cr./d_{p_2}/h_{s_1}/R_2	0.166	467.3	599.0
	0.333	869.1	844.0
	0.500	1248.2	1089.0
	0.666	1609.2	1373.0
	0.900	2104.5	2015.0
LSP/Cr./d_{p_2}/h_{s_1}/R_3	0.250	709.2	748.0
	0.333	914.8	884.0
	0.500	1313.8	1182.0
	0.666	1693.9	1481.0
	0.900	2215.3	2242.0
LSP/Cr.d_{p_2}/h_{s_1}/R_4	0.150	484.1	640.0
	0.300	895.9	980.0
	0.450	1286.1	1280.0
	0.600	1660.0	1550.0
	0.850	2263.9	2284.0

contd...

TABLE- 7.A_3 (Contd.)

1	2	3	4
LSP/Ba./d_{p_2}/h_{s_1}/R_1	0.150	649.2	775.0
	0.250	1022.9	980.0
	0.400	1551.6	1388.0
	0.500	1894.8	1680.0
	0.533	2003.7	1754.0
	0.650	2392.5	2490.0
	0.850	3036.0	3904.0
LSP/Ba./d_{p_2}/h_{s_1}/R_2	0.200	941.2	1061.0
	0.300	1351.2	1482.0
	0.400	1745.0	1920.0
	0.500	2131.0	2406.0
	0.650	2690.5	2952.0
	0.800	3236.0	4060.0
LSP/Ba./d_{p_2}/h_{s_1}/R_3	0.150	790.3	899.0
	0.250	1245.3	1482.0
	0.350	1678.8	1890.0
	0.467	2163.7	2395.0
	0.550	2509.7	2910.0
	0.666	2973.9	3430.0
	0.833	3631.0	4700.0
LSP/Ba./d_{p_2}/h_{s_1}/R_4	0.200	1092.4	1430.0
	0.300	1568.3	1810.0
	0.400	2025.3	2355.0
	0.600	2905.6	3295.0
	0.850	3962.6	5110.0

Contd...

TABLE- 7.A_3 (Contd.)

1	2	3	4
LSP/I/d_{p_2}/h_{s_1}/R_1	0.200	1054.8	666.0
	0.333	1662.9	980.0
	0.500	2388.1	1605.0
	0.650	3015.2	1985.0
	0.750	3423.0	2500.0
	0.833	3759.1	3505.0
LSP/I/d_{p_2}/h_{s_1}/R_2	0.250	1520.8	727.0
	0.333	1961.6	980.0
	0.416	2389.4	1278.0
	0.633	3474.6	1985.0
	0.750	4038.1	2650.0
LSP/I/d_{p_2}/h_{s_1}/R_3	0.217	1436.1	830.0
	0.400	2471.1	1182.0
	0.500	3017.7	1550.0
	0.666	3890.5	2300.0
	0.850	4835.0	3460.0
LSP/I/d_{p_2}/h_{s_1}/R_4	0.200	1393.4	925.0
	0.350	2295.9	1332.0
	0.550	3432.2	2015.0
	0.700	4252.9	2870.0
	0.850	5054.5	4180.0

T A B L E- 7.B_3

Verification of the correlation.

Run No.	$\frac{h_{pa}}{h_s}$	ΔP_T, Kg./M^2 Calculated	Experimental
1	2	3	4
$GSP/D/d_{p_1}/h_{s_1}/R_1$	0.166	137.1	244.0
	0.333	325.0	371.0
	0.500	537.5	565.0
	0.666	766.6	809.0
	0.833	1011.8	1352.0
$GSP/D/d_{p_1}/h_{s_1}/R_2$	0.200	295.1	339.0
	0.333	555.5	565.0
	0.500	918.8	1032.0
	0.600	1150.7	1523.0
	0.666	1310.5	1944.0
$GSP/D/d_{p_1}/h_{s_1}/R_3$	0.150	315.4	416.0
	0.250	596.0	475.0
	0.400	1065.6	753.0
	0.500	1406.0	1215.0
	0.650	1945.4	2178.0
$GSP/D/d_{p_1}/h_{s_1}/R_4$	0.166	498.2	665.0
	0.300	1035.4	1128.0
	0.400	1480.6	1990.0
	0.500	1953.3	3205.0

Contd...

TABLE- 7.B3 (Contd.)

1	2	3	4
$GSP/D/d_{p_2}/h_{s_1}/R_1$	0.200	164.6	155.0
	0.300	271.8	236.5
	0.400	388.6	387.0
	0.500	512.7	475.0
	0.600	642.2	813.0
	0.700	777.9	971.0
	0.866	1013.2	1610.0
$GSP/D/d_{p_2}/h_{s_1}/R_2$	0.133	172.7	186.0
	0.200	286.2	303.0
	0.333	538.9	486.0
	0.500	891.4	764.0
	0.650	1233.4	1375.0
	0.833	1678.1	2200.0
$GSP/D/d_{p_2}/h_{s_1}/R_3$	0.200	418.8	428.0
	0.333	788.2	605.0
	0.500	1303.9	1220.0
	0.666	1859.5	2095.0
	0.766	2211.7	2780.0
$GSP/D/d_{p_2}/h_{s_1}/R_4$	0.200	571.8	660.0
	0.333	1076.5	1428.0
	0.500	1780.8	2245.0
	0.666	2539.7	3210.0

Contd...

TABLE- 7.B3 (Contd.)

1	2	3	4
$GSP/D/d_{p_3}/h_{s_1}/R_1$	0.150	102.2	137.0
	0.300	241.5	215.5
	0.500	455.6	402.0
	0.650	630.5	787.0
	0.800	815.4	1208.0
	0.900	944.3	1896.0
$GSP/D/d_{p_3}/h_{s_1}/R_2$	0.166	192.4	141.0
	0.333	456.0	255.0
	0.500	754.3	532.0
	0.650	1043.9	1060.0
	0.750	1246.9	1743.0
	0.900	1563.3	2490.0
$GSP/D/d_{p_3}/h_{s_1}/R_3$	0.166	287.6	170.6
	0.250	478.3	265.0
	0.400	855.2	509.0
	0.500	1128.2	789.0
	0.666	1609.1	1670.0
	0.866	2229.1	2815.0
$GSP/D/d_{p_3}/h_{s_1}/R_4$	0.200	510.9	254.5
	0.333	961.9	606.0
	0.500	1591.0	853.0
	0.633	2130.1	1590.0
	0.800	2847.9	2545.0
	0.900	3297.5	3545.0

Contd...

TABLE- 7.B_3 (Contd.)

1	2	3	4
$GSP/D/d_{p_4}/h_{s_1}/R_1$	0.250	171.2	168.0
	0.400	306.3	254.0
	0.500	404.0	385.0
	0.666	576.2	617.5
	0.750	667.8	982.0
	0.850	780.0	1220.0
	0.900	837.3	1813.0
$GSP/D/d_{p_4}/h_{s_1}/R_2$	0.100	98.3	124.1
	0.200	232.4	173.5
	0.333	437.5	313.5
	0.500	723.7	559.0
	0.616	936.4	928.0
	0.700	1097.7	1006.0
	0.800	1295.2	1663.0
	0.883	1464.0	2390.0
$GSP/D/d_{p_4}/h_{s_1}/R_3$	0.166	268.2	153.0
	0.350	675.1	372.5
	0.500	1051.2	672.0
	0.600	1316.7	1138.0
	0.700	1594.7	1787.0
	0.833	1978.9	2370.0
$GSP/D/d_{p_4}/h_{s_1}/R_4$	0.166	378.1	368.5
	0.333	896.1	616.0
	0.500	1482.5	1028.0
	0.600	1856.8	1700.0
	0.750	2450.3	2613.0

TABLE- 7.B_3 (Contd.)

1	2	3	4
GSP/Cr./d_{p_2}/h_{s_1}/R_1	0.166	146.7	200.5
	0.300	305.0	310.0
	0.500	575.2	613.0
	0.750	950.7	914.0
	0.850	1110.3	1645.0
GSP/Cr./d_{p_2}/h_{s_1}/R_2	0.200	285.6	245.5
	0.250	376.9	306.5
	0.416	709.6	510.0
	0.500	889.2	623.0
	0.600	1113.7	909.0
	0.800	1591.5	2033.0
GSP/Cr./d_{p_2}/h_{s_1}/R_3	0.183	391.9	306.5
	0.250	578.4	385.0
	0.400	1034.4	564.0
	0.500	1364.6	941.0
	0.666	1946.3	1800.0
	0.750	2255.7	2605.0
GSP/Cr./d_{p_2}/h_{s_1}/R_4	0.166	484. 4	420.0
	0.250	805.1	508.0
	0.400	1439.9	790.0
	0.500	1899.6	1343.0
	0.600	2379.0	1960.0
	0.750	3139.8	3620.0

Contd..

TABLE- 7.B_3 (Contd.)

1	2	3	4
GSP/Ba./d_{p_2}/h_{s_1}/R_1	0.200	255.2	347.0
	0.250	336.7	438.0
	0.450	697.7	711.0
	0.500	794.5	782.0
	0.700	1205.0	1417.0
	0.800	1422.0	2445.0
GSP/Ba./d_{p_2}/h_{s_1}/R_2	0.250	579.7	694.0
	0.400	1036.9	1023.0
	0.500	1367.9	1443.0
	0.650	1892.7	1605.0
	0.750	2260.9	2560.0
GSP/Ba./d_{p_2}/h_{s_1}/R_3	0.200	662.9	455.0
	0.300	1094.3	787.0
	0.400	1564.6	1240.0
	0.500	2064.1	1825.0
	0.600	2585.2	2450.0
	0.700	3131.0	3415.0
GSP/Ba./d_{p_2}/h_{s_1}/R_4	0.200	938.0	700.0
	0.250	1238.3	926.0
	0.400	2214.2	1599.0
	0.500	2921.2	2875.0
	0.600	3658.6	4225.0

Contd..

TABLE- $7.B_3$ (Contd.)

1	2	3	4
$GSP/I/d_{p_2}/h_{s_1}/R_1$	0.200	355.8	188.2
	0.400	839.7	581.0
	0.500	1107.9	980.4
	0.700	1680.6	1381.0
	0.833	2085.4	2070.0
$GSP/I/d_{p_2}/h_{s_1}/R_2$	0.200	594.6	225.0
	0.400	1403.5	599.0
	0.500	1851.4	997.6
	0.650	2562.0	1180.0
	0.750	3060.2	1821.0
$GSP/I/d_{p_2}/h_{s_1}/R_3$	0.166	678.9	240.0
	0.250	1128.5	464.0
	0.400	2018.1	843.4
	0.500	2662.6	1476.0
	0.650	3684.2	2082.0
$GSP/I/d_{p_2}/h_{s_1}/R_4$	0.166	958.4	323.0
	0.333	2272.1	775.4
	0.450	3301.6	1304.0
	0.500	3758.5	1683.0
	0.600	4707.1	2006.0

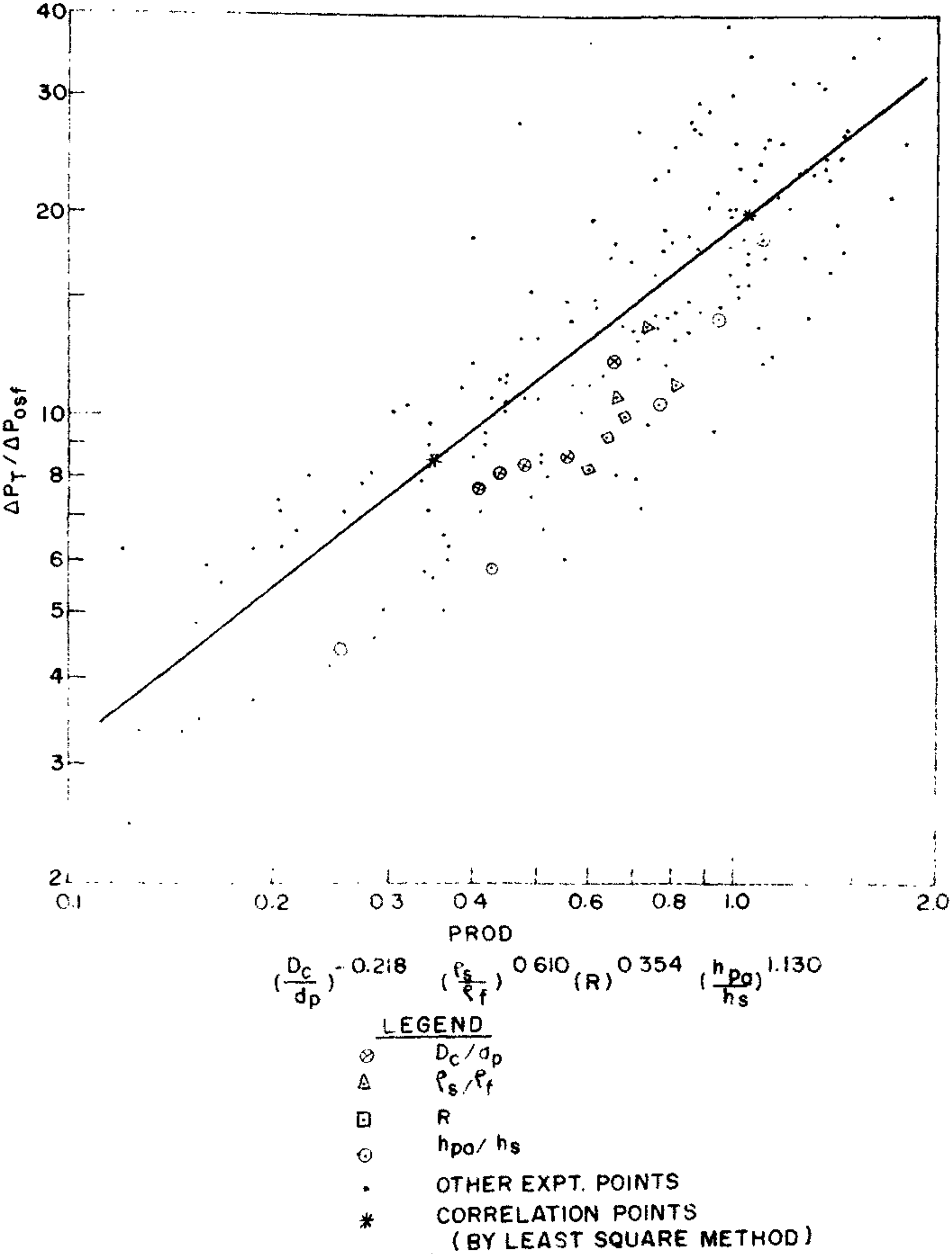


FIG 7. A_1 RELATION OF $\Delta P_T/\Delta P_{osf}$ WITH SYSTEM VARIABLES.

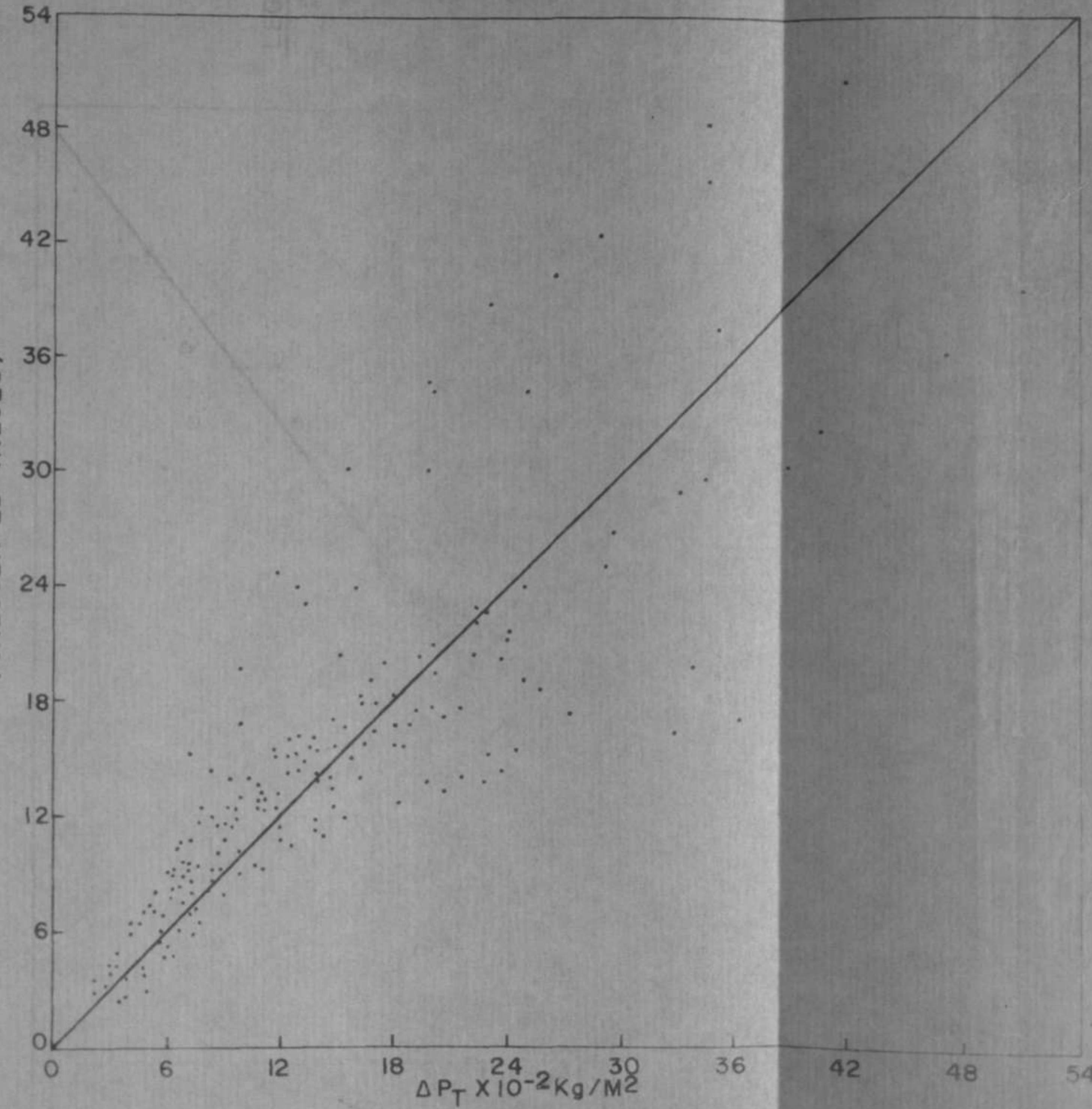


FIG. 7. A_2 COMPARISON OF SEMIFLUIDIZED BED PRESSURE DROP.

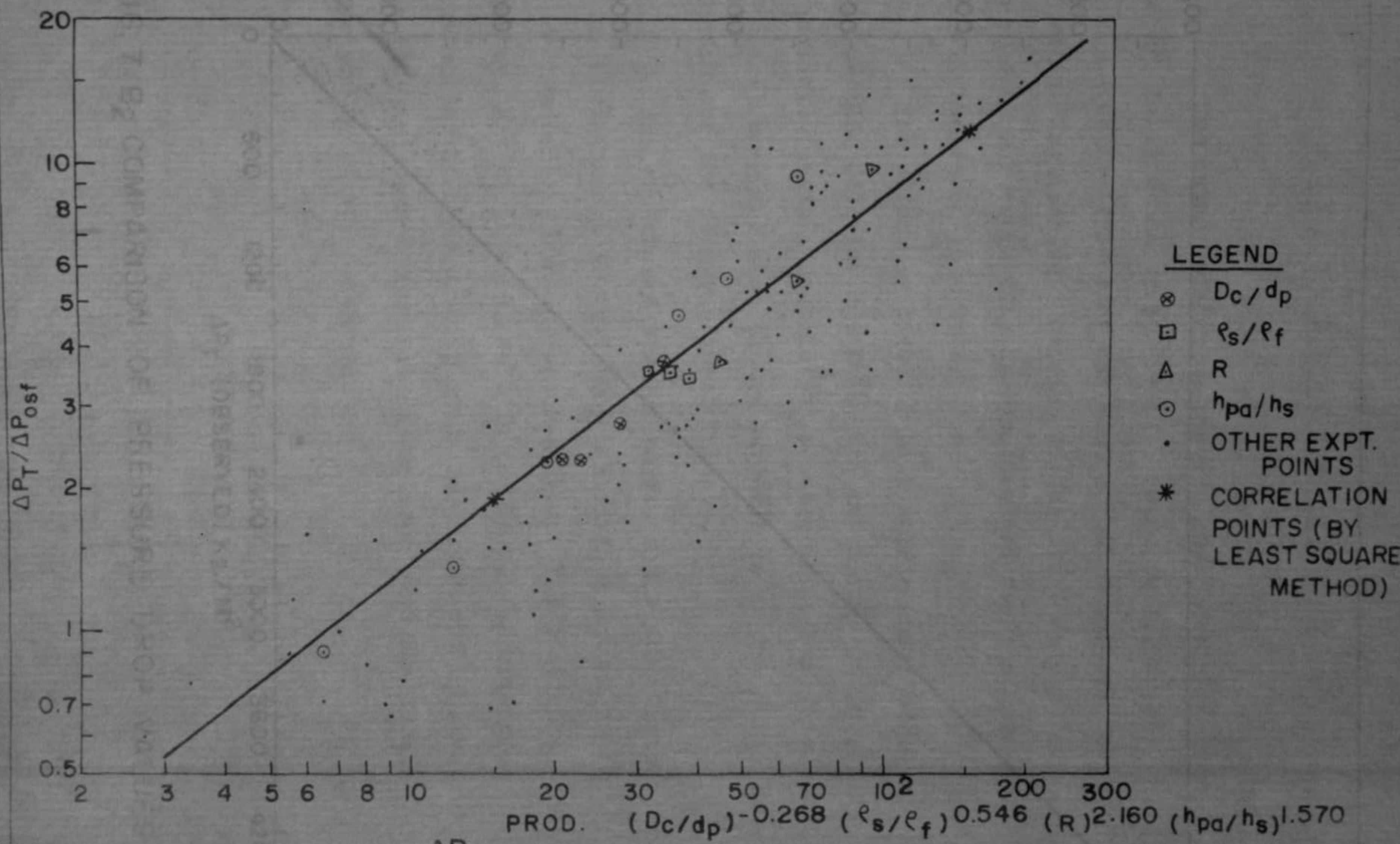


FIG. 7 B_1 RELATION OF $\frac{\Delta P_T}{\Delta P_{osf}}$ WITH SYSTEM VARIABLES.

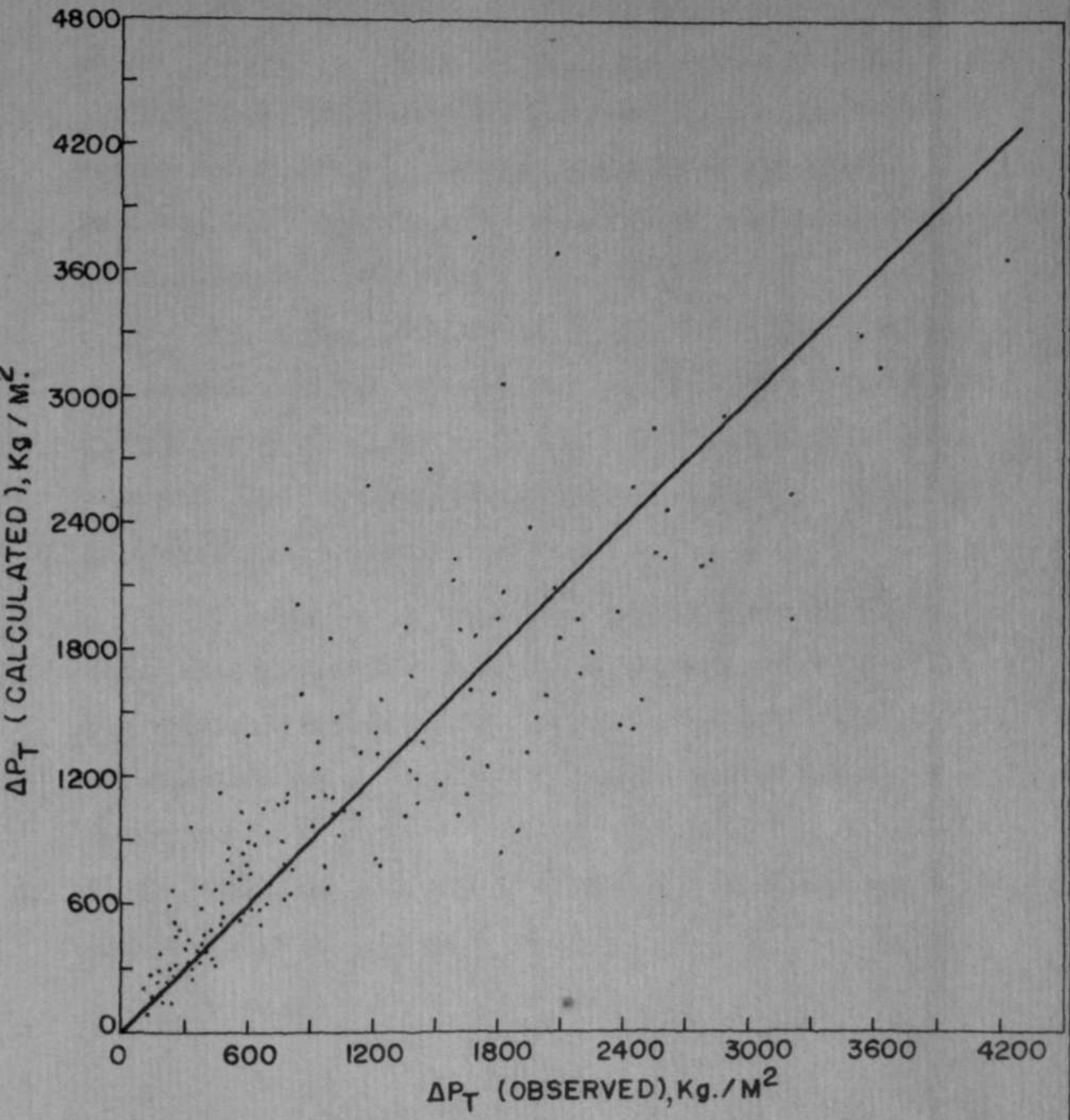


FIG. 7. B_2 COMPARISON OF PRESSURE DROP VALUES.

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A P P E N D I X - A

CALIBRATION DATA

T A B L E- 1.

Data for Calibration of Rotameter (Lower Range)

Sl. No.	Rotameter reading	Water flowrate, Kg/Hr.
1	3.0	10.8
2	5.0	20.0
3	6.0	24.6
4	8.0	30.0
5	10.0	36.0
6	15.0	55.5
7	20.0	75.0
8	25.0	88.0
9	30.0	108.0
10	40.0	142.0
11	50.0	174.0
12	60.0	209.0
13	70.0	242.0
14	80.0	276.0
15	90.0	312.0
16	100.0	343.0

T A B L E- 2.

Data for Calibration of Rotameter (Higher Range)

Sl. No.	Rotameter reading	Water flowrate Kg./Hr.
1	10.0	207.0
2	12.0	243.0
3	15.0	301.5
4	17.0	334.5
5	20.0	388.5
6	21.0	405.0
7	23.0	438.0
8	25.0	466.0
9	27.0	500.0
10	29.0	534.0
11	31.0	570.0
12	32.0	584.0
13	34.0	616.0

TABLE- 3.

Data for Calibration of Orificemeter (Lower Range)

Sl. No.	Manometer head		Air flow rate	
	ΔH_1 (Cms of CCl_4)	$\sqrt{\Delta H_1}$ (Cms.)$^{\frac{1}{2}}$ of CCl_4	m^3/hr	W Kg./hr.
1.	2.6	1.610	0.70	1.638
2.	3.6	1.900	0.96	2.245
3.	5.0	2.235	1.18	2.760
4.	6.9	2.625	1.44	3.370
5.	8.4	2.900	1.70	3.980
6.	10.2	3.195	1.92	4.495
7.	12.5	3.540	2.14	5.005
8.	14.9	3.860	2.40	5.610
9.	20.5	4.530	2.88	6.740
10.	26.1	5.100	3.32	7.765
11.	34.6	5.890	3.84	8.990
12.	41.5	6.440	4.32	10.100
13.	51.7	7.190	4.80	11.220
14.	59.8	7.730	5.24	12.250
15.	70.2	8.390	5.76	13.500
16.	81.1	9.005	6.25	14.620

T A B L E- 4.

Data for Calibration of Orificemeter (Higher Range)

Sl. No.	Manometer head		Air flow-rate	
	ΔH_1 (Cms.of Hg.)	$\sqrt{\Delta H_1}$ (Cms.)$^{\frac{1}{2}}$ of Hg.	Q m^3/hr.	W Kg./hr.
1	1.20	1.094	1.92	4.495
2	1.50	1.224	2.14	5.005
3	1.70	1.302	2.40	5.610
4	2.50	1.580	2.88	6.740
5	3.10	1.760	3.32	7.765
6	4.10	2.022	3.84	8.990
7	4.70	2.165	4.32	10.100
8	6.15	2.480	4.80	11.220
9	6.80	2.605	5.24	12.250
10	8.10	2.844	5.76	13.500
11	9.40	3.065	6.25	14.620
12	10.80	3.285	6.72	15.720
13	12.40	3.520	7.20	16.850
14	14.80	3.850	7.95	18.600
15	17.40	4.170	8.64	20.200
16	20.60	4.545	9.60	22.450
17	23.70	4.865	10.30	24.100
18	26.50	5.150	11.04	25.850
19	31.50	5.610	12.04	28.200
20	36.90	6.070	13.20	30.850
21	42.70	6.540	14.40	33.700
22	49.10	7.010	15.62	36.600
23	55.80	7.450	16.85	39.400
24	62.00	7.875	18.00	42.100
25	69.30	8.340	19.20	44.950

T A B L E- 5.

Variation of pressure drop through the restraint with air flow rate.

Sl. No.	Orifice pressure drop				Air flow rate Kg./Hr.	Pressure drop		
	ΔH_1 Cms.		$\sqrt{\Delta H_1}$ (Cms.)$^{\frac{1}{2}}$			ΔH_2 Cms.		ΔP Kg./M^2
1.	1.2	CCl_4	1.095	CCl_4	0.70	0.7	CCl_4	11.4
2.	2.9	"	1.702	"	1.75	1.3	"	21.2
3.	4.4	"	2.100	"	2.50	1.8	"	29.4
4.	6.3	"	2.510	"	3.25	2.4	"	39.1
5.	9.1	"	3.020	"	4.20	3.2	"	52.1
6.	13.2	"	3.635	"	5.30	4.2	"	68.5
7.	16.8	"	4.100	"	5.98	5.2	"	84.7
8.	21.8	"	4.660	"	6.96	6.4	"	104.2
9.	30.7	"	5.550	"	8.50	8.6	"	140.2
10.	40.9	"	6.400	"	10.00	11.0	"	179.3
11.	49.8	"	7.050	"	11.12	13.1	"	213.5
12.	6.0	Hg.	2.448	Hg.	11.40	14.1	"	230.0
13.	8.2	"	2.864	"	13.70	18.6	"	303.0
14.	11.0	"	3.320	"	16.20	24.2	"	394.5
15.	13.8	"	3.715	"	18.40	31.3	"	510.0
16.	16.8	"	4.100	"	20.50	39.5	"	644.0
17.	20.0	"	4.470	"	22.50	47.4	"	773.0
18.	24.6	"	4.960	"	25.25	59.5	"	970.0
19.	25.8	"	5.085	"	25.90	65.5	"	1068.0

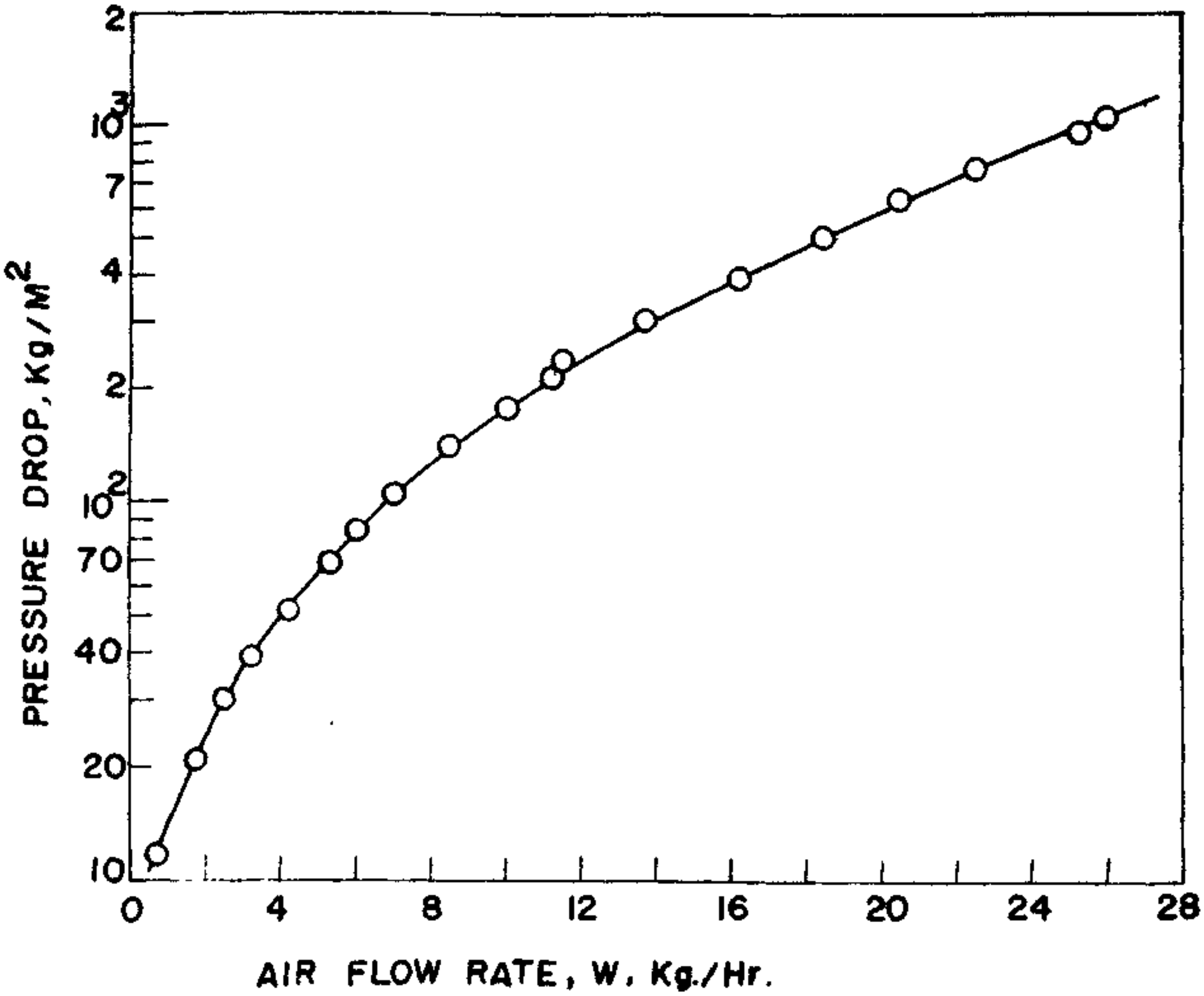

FIG. 1. VARIATION OF PRESSURE DROP THROUGH THE RESTRAINT WITH AIR FLOW RATE.

A P P E N D I X - B

EXPERIMENTAL DATA

VARIATION OF PRESSURE DROP AND PACKED BED FORMATION WITH FLUID MASS VELOCITY

TABLE- 1.

Run No.LSP/D/d_{p_1}/h_{s_1}/R_1 Average fluid temp.=23°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1		2	3	4	5	6
1	1.2	CCl_4	19.6	15800	-	-
2	2.0	"	32.6	29600	-	-
3	3.0	"	48.9	43450	-	-
4	5.2	"	84.7	71100	-	-
5	9.8	"	159.8	104800	-	-
6	13.0	"	212.0	138200	-	-
7	15.7	"	256.0	173800	-	-
8	17.9	"	292.0	207500	-	-
9	25.4	"	414.0	274500	-	-
10	32.3	"	526.0	343500	-	-
11	4.2	Hg.	571.0	440500	2.0	0.333
12	5.4	"	734.0	460000	3.0	0.500
13	6.4	"	870.0	494000	3.6	0.600
14	8.2	"	1116.0	535000	4.5	0.750
15	10.3	"	1400.0	582000	5.3	0.883

TABLE- 2.

Run No.LSP/D/d_{p_1}/h_{s_1}/R_2 Average fluid temp.=25°C.

1	2		3	4	5	6
1	2.4	CCl_4	39.2	37550	-	-
2	5.3	"	86.5	71100	-	-
3	10.1	"	164.7	104800	-	-
4	15.1	"	246.0	138200	-	-
5	18.1	"	295.0	173800	-	-
6	23.9	"	390.0	241000	-	-
7	35.2	"	574.0	345500	-	-
8	43.0	"	700.0	413000	-	-
9	5.4	Hg.	734.0	514000	2.0	0.333
10	6.9	"	939.0	549000	3.6	0.600
11	8.1	"	1101.0	582000	4.2	0.700
12	9.7	"	1320.0	618000	4.8	0.800
13	11.0	"	1495.0	651000	5.1	0.850

TABLE-3.

Run No.LSP/D/d_{p_1}/h_{s_1}/R_3 Average fluid temp.=27°C

Sl. No.	ΔH Cms.	ΔP_T Kg/M^2	G Kg/Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1.	2.	3.	4.	5.	6.
1.	2.0 CCl_4	32.6	37550	-	-
2.	5.0 "	81.5	71100	-	-
3.	9.5 "	154.9	104800	-	-
4.	15.0 "	244.5	138200	-	-
5.	18.3 "	298.0	173800	-	-
6.	28.5 "	465.0	274500	-	-
7.	5.6 Hg.	761.0	549000	1.8	0.300
8.	7.1 "	965.0	582000	3.3	0.550
9.	9.1 "	1238.0	618000	4.2	0.700
10.	12.0 "	1630.0	685000	5.1	0.850

TABLE-4.

Run No.LSP/D/d_{p_1}/h_{s_1}/R_4 Average fluid temp.=29°C.

1.	2.	3.	4.	5.	6
1.	2.6 CCl_4	42.4	37550	-	-
2.	5.6 "	91.3	71100	-	-
3.	10.8 "	176.0	104800	--	-
4.	16.4 "	267.5	138200	-	-
5.	19.8 "	322.5	173800	-	-
6.	20.5 "	334.0	274500	-	-
7.	47.8 "	780.0	446000	-	-
8.	6.0 Hg.	816.0	576000	1.8	0.300
9.	7.1 "	965.0	604500	2.7	0.450
10.	9.1 "	1238.0	651000	3.8	0.633
11.	11.2 "	1522.0	685000	5.0	0.833
12.	16.5 "	2244.0	774000	5.7	0.950

TABLE- 5.

Run No.LSP/D/d_{p1}/h_{s2}/R_1 Average fluid temp.= 22°C.

Sl. No.	ΔH Cms.		ΔP_T Kg/M^2	G Kg/Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1.	2.		3.	4.	5.	6.
1	3.6	CCl_4	58.6	37550	-	-
2	7.8	"	127.0	71100	-	-
3	14.4	"	234.5	104800	-	-
4	20.4	"	332.5	138200	-	-
5	24.0	"	391.0	173800	-	-
6	32.2	"	525.0	241000	-	-
7	5.1	Hg.	694.0	446000	2.4	0.300
8	6.6	"	897.0	480000	3.6	0.450
9	8.6	"	1170.0	514000	4.5	0.575
10	10.6	"	1440.0	549000	5.6	0.700
11	12.4	"	1688.0	582000	6.4	0.800
12	15.5	"	2105.0	651000	7.2	0.900

TABLE- 6.

Run No.LSP/D/d_{p1}/h_{s2}/R_2 Average fluid temp.= 24°C

1.	2.		3.	4.	5.	6.
1	3.6	CCl_4	58.6	37550	-	-
2	7.8	"	127.0	71100	-	-
3	15.1	"	246.0	104800	-	-
4	20.3	"	331.0	138200	-	-
5	31.3	"	510.0	207500	-	-
6	42.1	"	686.5	274500	-	-
7	58.3	"	950.0	379000	-	-
8	7.1	Hg.	965.0	514000	2.8	0.350
9	8.7	"	1182.0	549000	4.0	0.500
10.	10.8	"	1470.0	582000	5.0	0.625
11	12.7	"	1728.0	618000	6.0	0.750
12	15.7	"	2135.0	685000	7.0	0.875

TABLE- 7

Run No.LSP/D/$d_{p_1}/h_{s_2}/R_3$ Average fluid temp.=26°C

Sl. No.	ΔH Cms.	ΔP_T Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	3.9 CCl_4	63.5	37550	-	-
2	7.9 "	128.8	71100	-	-
3	15.3 "	249.5	104800	-	-
4	23.3 "	380.0	138200	-	-
5	31.9 "	520.0	207500	-	-
6	55.3 "	901.0	343500	-	-
7	7.5 Hg.	1020.0	549000	2.0	0.250
8	9.2 "	1251.0	582000	3.2	0.400
9	11.6 "	1578.0	618000	4.8	0.600
10	13.2 "	1795.0	651000	5.4	0.675
11	15.1 "	2055.0	687000	6.0	0.750
12	18.9 "	2570.0	817000	7.2	0.900

TABLE- 8

Run No.LSP/D/$d_{p_1}/h_{s_2}/R_4$ Average fluid temp.=28°C

1	2	3	4	5	6
1	5.2 CCl_4	84.8	37550	-	-
2	12.7 "	207.0	71100	-	-
3	25.3 "	413.0	104800	-	-
4	36.6 "	596.0	138200	-	-
5	6.5 Hg	885.0	379000	-	-
6	8.7 "	1183.0	480000	-	-
7	11.3 "	1538.0	549000	0.5	0.063
8	13.6 "	1850.0	582000	1.8	0.225
9	16.2 "	2204.0	618000	3.0	0.375
10	21.7 "	2952.0	685000	5.2	0.650
11	25.1 "	3415.0	765000	6.4	0.800

TABLE- 9

Run No.LSP/D/d_{p_1}/h_{s_3}/R_1 Average fluid temp.=23°C.

Sl.No.	ΔH Cms.		ΔP_T Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	5.4	CCl_4	88.0	37550	-	-
2	12.7	"	207.0	71100	-	-
3	24.6	"	401.0	104800	-	-
4	3.1	Hg.	421.0	274500	-	-
5	3.5	"	476.0	343500	-	-
6	6.0	"	816.0	426500	2.0	0.200
7	7.3	"	994.0	454500	3.0	0.300
8	9.3	"	1265.0	480000	4.5	0.450
9	11.7	"	1590.0	514000	5.8	0.580
10	13.3	"	1810.0	549000	7.0	0.700
11	17.9	"	2435.0	618000	8.4	0.840
12	22.1	"	3005.0	685000	9.0	0.900

TABLE- 10

Run No.LSP/D/d_{p_1}/h_{s_3}/R_2 Average fluid temp.=25°C

1	2		3	4	5	6
1	5.8	CCl_4	94.5	37550	-	-
2	11.7	"	191.0	71100	-	-
3	23.8	"	388.0	104800	-	-
4	32.4	"	529.0	138200	-	-
5	4.0	Hg.	544.0	274500	-	-
6	4.7	"	640.0	343500	-	-
7	6.5	"	885.0	480000	1.0	0.100
8	9.9	"	1348.0	514000	3.5	0.350
9	11.9	"	1620.0	549000	4.5	0.450
10	13.9	"	1890.0	582000	5.5	0.550
11	16.4	"	2230.0	618000	6.5	0.650
12	20.6	"	2800.0	685000	8.0	0.800
13	24.6	"	3345.0	722000	9.1	0.910

TABLE- 11.

Run No.LSP/D/d_{p_1}/h_{s3}/R_3 Average fluid temp.=27°C

Sl.No.	ΔH Cms.	ΔP_T Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	5.7 CCl_4	93.0	37550	-	-
2	12.7 "	207,0	71100	-	-
3	26.5 "	431.5	104800	-	-
4	34.9 "	569.0	138200	-	-
5	5.7 Hg.	775.0	379000	-	-
6	6.9 "	938.0	446000	-	-
7	7.9 "	1075.0	500000	-	-
8	11.1 "	1510.0	535000	1.5	0.150
9	12.7 "	1728.0	563500	2.5	0.250
10	14.2 "	1930.0	582000	3.5	0.350
11	17.6 "	2395.0	618000	5.2	0.520
12	22.7 "	3085.0	685000	7.0	0.700
13	26.6 "	3620.0	706000	8.6	0.860

TABLE- 12.

Run No.LSP/D/d_{p_1}/h_{s3}/R_4 Average fluid temp.= 28°C

1	2	3	4	5	6
1	7.9 CCl_4	128.8	37550	--	--
2	17.9 "	292.0	71100	--	--
3	32.7 "	534.0	104800	--	--
4	49.6 "	809.0	138200	--	--
5	6.0 Hg.	816.0	274500	--	--
6	6.9 "	939.0	309000	--	--
7	9.4 "	1280.0	379000	--	--
8	12.7 "	1730.0	480000	--	--
9	14.1 "	1920.0	529500	--	--
10	17.5 "	2380.0	569000	1.3	0.130
11	19.1 "	2600.0	590000	2.0	0.200
12	21.4 "	2910.0	618000	3.5	0.350
13	25.9 "	3625.0	651000	4.8	0.480
14	28.5 "	3880.0	685000	6.2	0.620
15	41.5 "	5650.0	730000	9.2	0.920

TABLE- 13

Run No.LSP/D/d_{p_1}/h_{s_4}/R_1 Average fluid temp.= 26°C

Sl.No.	ΔH Cms.	ΔP_T Kg/M²	G Kg/Hr.M²	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	0.6 Hg.	81.6	37550	-	-
2	1.2 "	163.0	71100	-	-
3	2.1 "	286.0	104800	-	-
4	2.9 "	394.0	138200	-	-
5	3.9 "	530.0	173800	-	-
6	4.5 "	612.0	207500	-	-
7	6.1 "	830.0	274500	-	-
8	7.6 "	1033.0	343500	-	-
9	12.2 "	1660.0	426500	3.0	0.250
10	14.8 "	2015.0	454500	4.8	0.400
11	17.2 "	2340.0	480000	6.3	0.525
12	20.8 "	2830.0	514000	7.8	0.650
13	23.7 "	3220.0	555000	9.3	0.775
14	29.2 "	3975.0	618000	10.8	0.900

TABLE- 14

Run No.LSP/D/d_{p_1}/h_{s_4}/R_2 Average fluid temp.= 28°C

1	2	3	4	5	6
1	0.5 Hg.	68.0	37550	-	-
2	1.1 "	148.0	71100	-	-
3	1.9 "	258.5	104800	-	-
4	2.5 "	340.0	138200	-	-
5	3.9 "	530.0	207500	-	-
6	5.7 "	775.0	274500	-	-
7	7.5 "	1020.0	343500	-	-
8	9.5 "	1291.0	426600	-	-
9	14.6 "	1985.0	494000	3.0	0.250
10	17.5 "	2380.0	521000	4.5	0.375
11	20.1 "	2735.0	549000	6.0	0.500
12	22.7 "	3085.0	582000	7.0	0.585
13	27.3 "	3715.0	730000	9.0	0.750
14	32.3 "	4400.0	685000	10.2	0.850

TABLE- 15

Run No.LSP/D/d_{p_1}/h_{s_4}/R_3 Average fluid temp.= 29°C

Sl.No.	ΔH Cms.	ΔP_T Kg/M^2	G Kg/Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	0.5 Hg.	68.0	37550	-	-
2	0.9 "	122.3	71100	-	-
3	1.9 "	258.5	104800	-	-
4	2.7 "	367.0	138200	-	-
5	3.9 "	530.0	207500	-	P
6	6.7 "	910.0	309000	-	-
7	9.7 "	1320.0	413000	-	-
8	11.9 "	1620.0	480000	-	-
9	16.0 "	2175.0	521000	1.5	0.125
10	18.6 "	2528.0	549000	2.7	0.225
11	23.2 "	3155.0	582000	4.5	0.375
12	26.4 "	3590.0	618000	6.0	0.500
13	33.1	4500.0	685000	8.4	0.700

TABLE- 16

Run No.LSP/D/d_{p_1}/h_{s_4}/R_4 Average fluid temp.=31°C

1	2	3	4	5	6
1	0.5 Hg.	68.0	37550	-	-
2	1.1 "	149.6	71100	-	-
3	2.1 "	286.0	104800	-	-
4	2.9 "	394.0	138200	-	-
5	4.5 "	611.0	207500	-	-
6	9.1 "	1238.0	343500	-	-
7	14.2 "	1930.0	480000	-	-
8	16.2 "	2200.0	529500	-	-
9	19.2 "	2610.0	563500	1.5	0.125
10	21.8 "	2960.0	582000	2.4	0.200
11	25.8 "	3505.0	618000	4.5	0.375
12	32.7 "	4450.0	685000	8.0	0.666
13	40,8 "	5550,0	711000	10.0	0.833

T A B L E- 17

Run No.LSP/D/d_{p_2}/h_{s_1}/R_1 Average fluid temp.=23°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	3.0 CCl_4	48.9	21720	-	-
2	6.2 "	101.0	37550	-	-
3	7.8 "	127.0	49400	-	-
4	8.4 "	137.0	63100	-	-
5	8.8 "	143.4	77000	-	-
6	9.0 "	146.7	90850	-	-
7	9.6 "	156.3	104800	-	-
8	10.2 "	166.0	124300	-	-
9	10.8 "	176.0	138200	-	-
10	11.2 "	182.5	152000	-	-
11	11.8 "	192.0	173800	-	-
12	12.3 "	200.4	185700	-	-
13	2.4 Hg.	326.0	241000	1.5	0.250
14	3.2 "	435.0	274500	2.4	0.400
15	4.7 "	639.0	288200	3.0	0.500
16	5.7 "	775.0	324000	4.0	0.666
17	7.6 "	1033.0	355000	4.8	0.800
18	10.0 "	1360.0	413000	5.5	0.916

T A B L E- 18

Run No.LSP/D/d_{p_2}/h_{s_1}/R_2 Average fluid temp.=25°C.

1	2	3	4	5	6
1	3.7 CCl_4	60.3	21720	-	-
2	6.3 "	102.7	37550	-	-
3	8.1 "	132.0	49400	-	-
4	9.2 "	150.0	71100	-	-
5	10.8 "	176.0	104800	-	-
6	12.4 "	202.0	138200	-	-
7	13.9 "	226.5	173800	-	-
8	15.5 "	252.5	207500	-	-
9	17.5 "	285.0	228000	-	-
10	23.9 "	389.5	248000	0.9	0.150
11	3.0 Hg.	408.0	274500	1.6	0.266
12	4.5 "	611.0	309000	2.5	0.416
13	5.8 "	789.0	343500	3.6	0.600
14	8.6 "	1170.0	379000	4.5	0.750
15	12.6 "	1713.0	446000	5.4	0.900

TABLE- 19

Run No.LSP/D/d_{p2}/h_{s1}/R_3 Average fluid temp.= 27°C

Sl.No.	ΔH Cms.	ΔP_{T} Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	3.7 CCl_4	60.2	21720	-	-
2	5.6 "	91.3	37550	-	-
3	8.0 "	130.5	49400	-	-
4	9.0 "	147.0	71100	-	-
5	10.4 "	169.5	104800	-	-
6	12.1 "	197.0	138200	-	-
7	14.1 "	230.0	173800	-	-
8	16.1 "	262.4	207500	-	-
9	18.1 "	295.0	241000	-	-
10	3.3 Hg.	449.0	317000	1.7	0.284
11	4.6 "	625.0	343500	2.5	0.416
12	6.8 "	925.0	379000	3.6	0.600
13	8.6 "	1170.0	413000	4.5	0.750
14	13.2 "	1793.0	480000	5.5	0.916

TABLE- 20

Run No.LSP/D/d_{p2}/h_{s1}/R_4 Average fluid temp.= 20°C

1	2	3	4	5	6
1	3.0 CCl_4	48.9	21720	-	-
2	6.1 "	99.5	37550	-	-
3	9.3 "	151.7	49400	-	-
4	10.3 "	168.0	71100	-	-
5	12.8 "	208.5	104800	-	-
6	15.5 "	252.5	138200	-	-
7	18.2 "	296.5	173800	-	-
8	21.3 "	347.5	207500	-	-
9	28.1 "	458.5	274500	-	-
10	33.5 "	545.5	288200	-	-
11	4.9 Hg.	666.0	343500	2.0	0.333
12	7.3 "	993.0	379000	3.3	0.550
13	9.4 "	1280.0	413000	4.0	0.666
14	12.0 "	1630.0	446000	4.8	0.800
15	16.3 "	2215.0	514000	5.5	0.916

TABLE- 21

Run No.LSP/D/d_{p2}/h_{s2}/R_1 Average fluid temp.=22.5°C

Sl.No.	ΔH Cms.		ΔP_T Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	4.1	CCl_4	66.8	21720	-	-
2	7.9	"	129.0	37550	-	-
3	10.9	"	178.0	49400	-	-
4	11.7	"	191.0	71100	-	-
5	13.1	"	214.0	104800	-	-
6	15.0	"	244.5	138200	-	-
7	16.9	"	276.0	173800	-	-
8	17.7	"	288.5	185700	-	-
9	18.7	"	305.0	199500	-	-
10	3.0	Hg.	408.0	248000	1.8	0.225
11	4.9	"	666.0	274500	3.2	0.400
12	7.3	"	993.0	309000	4.5	0.562
13	9.6	"	1306.0	343500	5.5	0.687
14	12.3	"	1670.0	379000	6.4	0.800
15	16.9	"	2300.0	446000	7.2	0.900

TABLE- 22

Run No.LSP/D/d_{p2}/h_{s2}/R_2 Average fluid temp.= 25°C

1	2		3	4	5	6
1	4.5	CCl_4	73.4	21720	-	-
2	6.8	"	111.0	37550	-	-
3	10.3	"	168.0	49400	-	-
4	12.3	"	200.5	71100	-	-
5	14.4	"	234.8	104800	-	-
6	17.0	"	277.5	138200	-	-
7	19.5	"	318.0	173800	-	-
8	22.0	"	359.0	207500	-	-
9	3.0	Hg.	408.0	274500	1.2	0.150
10	4.9	"	666.0	309000	2.5	0.312
11	7.3	"	993.0	343500	4.0	0.500
12	10.1	"	1372.0	379000	5.2	0.650
13	12.9	"	1754.0	413000	6.0	0.750
14	18.4	"	2485.0	480000	7.2	0.900

TABLE- 23

Run No.LSP/D/d_{p_2}/h_{s_2}/R_3 Average fluid temp.= 27°C

Sl.No.	ΔH Cms.	ΔP_t Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	4.6 CCl_4	75.0	21720	-	-
2	7.3 "	119.0	37550	-	-
3	11.1 "	181.0	49400	-	-
4	13.5 "	220.0	71100	-	-
5	16.3 "	266.0	104800	-	-
6	19.6 "	319.5	138200	-	-
7	26.3 "	429.0	207500	-	-
8	30.2 "	492.0	241000	-	-
9	4.1 Hg.	557.0	324000	1.5	0.187
10	6.0 "	816.0	343500	2.5	0.312
11	8.9 "	1210.0	379000	4.0	0.500
12	11.5 "	1562.0	413000	5.0	0.625
13	14.5 "	1970.0	446000	6.2	0.775
14	22.2 "	3020.0	514000	7.5	0.937

TABLE- 24

Run No.LSP/D/d_{p_2}/h_{s_2}/R_4 Average fluid temp.= 29°C

1	2	3	4	5	6
1	4.5 CCl_4	73.4	21720	-	-
2	8.5 "	138.7	37550	-	-
3	11.1 "	181.0	49400	-	-
4	14.9 "	243.0	71100	-	-
5	18.3 "	298.0	104800	-	-
6	22.8 "	372.0	138200	-	-
7	30.2 "	492.0	207500	-	-
8	39.7 "	646.5	274500	-	-
9	5.0 Hg.	680.0	343500	1.5	0.187
10	7.9 "	1074.0	379000	3.0	0.375
11	11.4 "	1550.0	413000	4.2	0.525
12	14.3 "	1943.0	446000	5.2	0.650
13	17.7 "	2405.0	480000	6.4	0.800
14	24.2 "	3290.0	549000	7.5	0.937

TABLE -25

Run No.LSP/D/$d_{p2}/h_{s3}/R_1$ Average fluid temp.=29°C.

Sl.No.	ΔH Cms.	ΔP_T Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	6.1 CCl_4	99.5	21720	-	-
2	9.4 "	153.2	37550	-	-
3	14.0 "	228.0	49400	-	-
4	16.2 "	264.0	71100	-	-
5	19.9 "	324.4	104800	-	-
6	23.4 "	381.5	138200	-	-
7	26.7 "	435.0	173800	-	-
8	30.1 "	490.5	207500	-	-
9	4.3 Hg.	585.0	254500	2.4	0.240
10	6.1 "	830.0	274500	3.5	0.350
11	8.6 "	1170.0	309000	5.0	0.500
12	11.9 "	1620.0	343500	6.5	0.650
13	15.2 "	2068.0	379000	7.5	0.750
14	18.7 "	2545.0	413000	8.4	0.840
15	25.1 "	3420.0	480000	9.4	0.940

TABLE- 26

Run No.LSP/D/ $d_{p2}/h_{s3}/R_2$ Average fluid temp.=31°C

1	2	3	4	5	6
1	5.7 CCl_4	93.0	21720	-	-
2	9.7 "	158.0	37550	-	-
3	14.7 "	240.0	49400	-	-
4	18.0 "	293.5	71100	-	-
5	22.1 "	360.0	104800	-	-
6	27.0 "	440.0	138200	-	-
7	3.7 Hg.	504.0	274500	1.0	0.100
8	6.4 "	871.0	309000	3.0	0.300
9	9.5 "	1291.0	343500	4.5	0.450
10	13.0 "	1770.0	379000	6.0	0.600
11	16.7 "	2272.0	413000	7.5	0.750
12	20.5 "	2790.0	446000	8.5	0.850
13	27.5 "	3744.0	514000	9.5	0.950

TABLE-27.

Run No.LSP/D/d_{p_2}/h_{s_3}/R_3 Average fluid temp.= 27.5°C

Sl.No.	ΔH Cms.	ΔP_T Kg/M^2	G Kg/Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	6.9 CCl_4	112.5	21720	-	-
2	11.6 "	189.0	37550	-	-
3	16.8 "	274.0	49400	-	-
4	20.3 "	331.0	71100	-	-
5	26.1 "	425.5	104800	-	-
6	32.6 "	531.0	138200	-	-
7	40.1 "	655.0	173800	-	-
8	6.1 Hg.	830.0	309000	1.3	0.130
9	9.7 "	1320.0	343600	3.0	0.300
10	14.0 "	1905.0	379000	5.0	0.500
11	18.0 "	2450.0	413000	6.5	0.650
12	22.1 "	3010.0	446000	7.5	0.750
13	26.6 "	3620.0	480000	8.5	0.850
14	36.1 "	4910.0	549000	9.5	0.950

TABLE- 28.

Run No.LSP/D/d_{p_2}/h_{s_3}/R_4 Average fluid temp.=29°C

1	2	3	4	5	6
1	9.7 CCl_4	158.0	21720	-	-
2	15.0 "	244.4	37550	-	-
3	21.2 "	346.0	49400	-	-
4	25.8 "	420.0	71100	-	-
5	33.7 "	550.0	104800	-	-
6	4.2 Hg.	571.0	241000	-	-
7	5.8 "	789.0	309000	-	-
8	7.2 "	980.0	331000	0.5	0.050
9	10.6 "	1490.0	357500	2.0	0.200
10	13.6 "	1850.0	379000	3.2	0.320
11	17.9 "	2435.0	413000	5.0	0.500
12	22.5 "	3060.0	446000	6.5	0.650
13	27.1 "	3685.0	480000	7.5	0.750
14	32.0 "	4350.0	514000	8.5	0.850
15	41.4 "	5640.0	582000	9.5	0.950

TABLE-29

Run No.LSP/D/d_{p2}/h_{s_4}/R_1 Average fluid temp.= 22°C

Sl.No.	ΔH Cms.		ΔP_{T_2} Kg/M^2	G Kg/Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1			2	3	4	5	6
1	9.7	CCl_4	158.1	21720	-	-
2	17.0	"	277.0	37550	-	-
3	21.6	"	352.0	49400	-	-
4	25.3	"	412.0	71100	-	-
5	31.2	"	509.0	104800	-	-
6	4.5	Hg.	611.5	228000	2.0	0.166
7	6.0	"	816.0	241000	3.0	0.250
8	8.9	"	1210.0	274500	5.4	0.450
9	13.1	"	1780.0	309000	7.2	0.600
10	17.0	"	2315.0	343500	8.5	0.708
11	22.0	"	2995.0	379000	9.6	0.800
12	29.5	"	4010.0	446000	11.0	0.917

TABLE- 30

Run No.LSP/D/d_{p2}/h_{s_4}/R_2 Average fluid temp.=24°C.

1	2		3	4	5	6
1	10.5	CCl_4	171.0	21720	-	-
2	13.2	"	215.5	37550	-	-
3	19.2	"	313.0	49400	-	-
4	22.0	"	358.5	71100	-	-
5	27.8	"	453.0	104800	-	-
6	35.5	"	579.0	138200	-	-
7	42.3	"	690.0	173800	-	-
8	6.5	Hg.	885.0	274500	2.0	0.166
9	10.0	"	1360.0	309000	4.5	0.375
10	14.0	"	1905.0	343500	6.5	0.542
11	19.2	"	2614.0	379000	8.0	0.666
12	23.9	"	3250.0	413000	9.0	0.750
13	28.5	"	3880.0	446000	10.0	0.833
14	38.2	"	5200.0	514000	11.5	0.958

TABLE- 31

Run No.LSP/D/d_{p_2}/h_{s_4}/R_3 Average fluid temp.=26°C

Sl.No.	ΔH Cms.		ΔP_T Kg/M^2	G $Kg/Hr.M^2$	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	10.7	CCl_4	174.2	21720	-	-
2	15.5	"	252.5	37550	-	-
3	21.2	"	346.0	49400	-	-
4	27.2	"	444.0	71100	-	-
5	36.3	"	592.0	104800	-	-
6	47.2	"	770.0	138200	-	-
7	58.3	"	950.0	173800	-	-
8	8.1	Hg.	1101.0	309000	1.2	0.100
9	12.4	"	1688.0	343500	3.6	0.300
10	17.5	"	2380.0	379000	6.0	0.500
11	22.9	"	3120.0	413000	7.5	0.625
12	28.3	"	3852.0	446000	9.0	0.750
13	33.1	"	4500.0	480000	10.0	0.833
14	43.9	"	5980.0	549000	11.5	0.958

TABLE- 32

Run No.LSP/D/d_{p_2}/h_{s_4}/R_4 Average fluid temp.= 28°C

1	2		3	4	5	6
1	10.6	CCl_4	173.0	21720	-	-
2	16.0	"	260.5	37550	-	-
3	22.7	"	370.0	49400	-	-
4	31.2	"	509.0	71100	-	-
5	42.1	"	686.0	104800	-	-
6	56.0		914.0	138200	-	-
7	7.2	Hg.	980.0	309000	-	-
8	10.7	"	1458.0	343500	1.5	0.125
9	16.2	"	2200.0	379000	4.0	0.333
10	22.1	"	3005.0	413000	6.3	0.525
11	28.1	"	3820.0	446000	8.0	0.666
12	32.8	"	4460.0	480000	9.0	0.750
13	39.1	"	5315.0	514000	10.3	0.817
14	49.2	"	6700.0	582000	11.5	0.958

TABLE- 33

Run No. $LSP/D/d_{p3}/h_{s_1}/R_1$ Average fluid temp.=21°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	3.6 CCl_4	58.6	9875	-	-
2	7.1 "	116.0	15800	-	-
3	7.3 "	119.0	29600	-	-
4	7.5 "	122.2	37550	-	-
5	7.9 "	129.0	49400	-	-
6	8.2 "	134.0	71100	-	-
7	8.7 "	142.0	90850	-	-
8	9.1 "	148.5	104800	-	-
9	21.5 "	350.5	117500	0.75	0.125
10	3.5 Hg.	476.0	152000	2.50	0.416
11	5.6 "	761.0	173800	3.50	0.583
12	10.1 "	1373.6	207500	4.50	0.750
13	15.2 "	2067.0	248000	5.20	0.866

TABLE- 34

Run No. $LSP/D/d_{p3}/h_{s_1}/R_2$ Average fluid temp.=23°C.

1	2	3	4	5	6
1	5.7 CCl_4	93.0	9875	-	-
2	6.8 "	111.0	15800	-	-
3	7.0 "	114.2	21720	-	-
4	7.6 "	124.0	37550	-	-
5	8.0 "	130.5	49400	-	-
6	8.2 "	134.0	71100	-	-
7	8.8 "	143.7	104800	-	-
8	9.2 "	150.0	124300	-	-
9	24.0 "	391.2	145100	0.75	0.125
10	5.0 Hg.	680.0	173800	2.40	0.400
11	6.7 "	910.0	207500	3.60	0.600
12	10.3 "	1400.0	241000	4.80	0.800
13	13.6 "	1850.0	274500	5.50	0.917

TABLE- 35.

Run No.LSP/D/d_{p_3}/h_{s_1}/R_3 Average fluid temp.=24°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	5.9 CCl_4	96.2	9875	-	-
2	7.1 "	116.0	15800	-	-
3	7.3 "	119.2	21720	-	-
4	7.5 "	122.2	37550	-	-
5	7.8 "	127.2	49400	-	-
6	8.2 "	133.8	71100	-	-
7	8.8 "	143.5	104800	-	-
8	9.5 "	155.0	138200	-	-
9	10.1 "	164.8	152000	-	-
10	30.1 "	490.0	173800	1.0	0.166
11	5.2 Hg.	707.0	207500	2.8	0.466
12	9.1 "	1238.0	241000	4.4	0.733
13	12.5 "	1700.0	274500	5.1	0.850
14	15.8 "	2148.0	309000	5.6	0.933

TABLE- 36.

Run No.LSP/D/d_{p_3}/h_{s_1}/R_4 Average fluid temp.=26°C.

1	2	3	4	5	6
1	5.9 CCl_4	96.2	9875	-	-
2	7.2 "	117.5	15800	-	-
3	7.3 "	119.2	21720	-	-
4	7.5 "	122.2	37550	-	-
5	7.8 "	127.2	49400	-	-
6	8.2 "	133.8	71100	-	-
7	8.8 "	143.5	104800	-	-
8	9.4 "	153.2	138200	-	-
9	10.7 "	174.5	173800	-	-
10	30.9 "	504.0	185700	0.75	0.125
11	5.4 Hg.	734.0	207500	2.25	0.375
12	8.2 "	1115.0	241000	3.80	0.633
13	12.1 "	1645.0	274500	4.80	0.800
14	15.2 "	2067.0	309000	5.30	0.883
15	18.9 "	2570.0	343500	5.80	0.966

TABLE- 37

Run No.LSP/D/d_{p_3}/h_{s_2}/R_1 Average fluid temp.=26°C

Sl.No.	ΔH Cms.	ΔP_T Kg/M^2	G Kg/Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	6.7 CCl_4	109.2	9875	-	-
2	9.4 "	153.2	15800	-	-
3	9.4 "	153.2	21720	-	-
4	9.6 "	156.6	37550	-	-
5	9.8 "	160.0	49400	-	-
6	10.2 "	166.2	71100	-	-
7	10.6 "	178.0	104800	-	-
8	25.8 "	420.0	124300	0.8	0.100
9	3.7 Hg.	503.0	152000	2.8	0.350
10	5.2 "	706.0	173800	4.0	0.500
11	9.5 "	1290.0	207500	6.0	0.750
12	13.2 "	1795.0	241000	7.0	0.875
13	17.0 "	2312.0	274500	7.5	0.938

TABLE- 38

Run No.LSP/D/d_{p_3}/h_{s_2}/R_2 Average fluid temp.=27°C

1	2	3	4	5	6
1	8.6 CCl_4	140.3	9875	-	-
2	9.6 "	156.6	15800	-	-
3	9.6 "	156.6	21720	-	-
4	9.8 "	160.0	37550	-	-
5	10.2 "	166.2	49400	-	-
6	10.4 "	169.4	71100	-	-
7	11.1 "	181.0	104800	-	-
8	12.1 "	197.2	138200	-	-
9	32.0 "	521.0	152000	1.0	0.125
10	4.1 Hg.	557.0	173800	2.6	0.325
11	7.6 "	1032.0	207500	4.4	0.550
12	12.3 "	1672.0	241000	6.3	0.787
13	15.7 "	2135.0	274500	7.0	0.875
14	20.4 "	2775.0	309000	7.6	0.950

TABLE- 39

Run No.LSP/D/d_{p_3}/h_{s_2}/R_3 Average fluid temp.=20.5°C

Sl.No.	ΔH Cms.	ΔP_{T} Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	7.7 CCl_4	125.6	9875	-	-
2	8.8 "	143.5	15800	-	-
3	9.2 "	150.0	21720	-	-
4	9.8 "	160.0	37550	-	-
5	10.2 "	166.2	49400	-	-
6	10.6 "	173.0	71100	-	-
7	11.5 "	187.5	104800	-	-
8	12.6 "	205.5	138200	-	-
9	23.0 "	375.0	160000	0.5	0.063
10	53.0 "	864.0	173800	1.5	0.188
11	6.9 Hg.	940.0	207500	4.0	0.500
12	12.6 "	1715.0	241000	6.0	0.750
13	17.3 "	2355.0	274500	7.0	0.875
14	22.5 "	3060.0	309000	7.5	0.938

TABLE- 40

Run No.LSP/D/d_{p_3}/h_{s_2}/R_4 Average fluid temp.=21.5°C

1	2	3	4	5	6
1	8.80 CCl_4	143.5	9875	-	-
2	9.25 "	151.0	15800	-	-
3	9.35 "	152.5	21720	-	-
4	9.90 "	161.5	37550	-	-
5	10.30 "	168.0	49400	-	-
6	10.70 "	174.5	71100	-	-
7	11.30 "	184.0	104800	-	-
8	12.10 "	197.2	138200	-	-
9	13.30 "	216.8	173800	-	-
10	2.80 Hg.	381.0	193700	1.5	0.188
11	4.90 "	666.0	207500	2.5	0.313
12	9.50 "	1291.0	241000	4.5	0.563
13	15.00 "	2040.0	274500	6.2	0.775
14	19.30 "	2625.0	309000	7.0	0.875
15	24.20 "	3295.0	343500	7.6	0.950

TABLE- 41

Run No.LSP/D/d_{p_3}/h_{s_3}/R_1 Average fluid temp.=23°C.

Sl.No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	10.5 CCl_4	171.0	9875	-	-
2	12.1 "	197.0	15800	-	-
3	12.5 "	204.0	21720	-	-
4	12.5 "	204.0	37550	-	-
5	12.6 "	205.5	49400	-	-
6	12.9 "	210.0	71100	-	-
7	13.5 "	220.0	90850	-	-
8	13.7 "	223.5	104800	-	-
9	2.2 Hg.	299.0	124300	1.6	0.160
10	3.6 "	489.5	138200	3.0	0.300
11	7.8 "	1061.0	173800	5.5	0.550
12	12.2 "	1660.0	207500	7.3	0.730
13	17.1 "	2324.0	241000	8.5	0.850
14	22.6 "	3075.0	274500	9.2	0.920

TABLE- 42

Run No.LSP/D/d_{p_3}/h_{s_3}/R_2 Average fluid temp.=25°C.

1	2	3	4	5	6
1	11.3 CCl_4	184.2	9875	-	-
2	12.1 "	197.0	15800	-	-
3	12.2 "	199.0	21720	-	-
4	12.4 "	202.0	37550	-	-
5	12.6 "	205.5	49400	-	-
6	13.2 "	215.0	71100	-	-
7	14.1 "	230.0	104800	-	-
8	18.9 "	308.0	138200	0.5	0.050
9	2.9 Hg.	394.0	156000	1.6	0.160
10.	5.1 "	694.0	173800	3.2	0.320
11	9.8 "	1332.0	207500	5.8	0.580
12	15.5 "	2105.0	241000	7.5	0.750
13	20.9 "	2840.0	274500	8.8	0.880
14	26.1 "	3550.0	309000	9.3	0.930

TABLE- 43

Run No.LSP/D/d_{p_3}/h_{s_3}/R_3 Average fluid temp.=27°C

Sl.No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	11.7	CCl_4	190.7	9875	-	-
2	12.1	"	197.1	15800	-	-
3	12.3	"	200.5	21720	-	-
4	12.5	"	204.0	37550	-	-
5	13.1	"	213.5	49400	-	-
6	13.5	"	220.0	71100	-	-
7	14.1	"	230.0	104800	-	-
8	14.9	"	242.8	138200	-	-
9.	15.5	"	252.4	160000	-	-
10	2.6	Hg.	354.0	179800	1.2	0.120
11	6.2	"	844.0	207500	3.6	0.360
12	11.8	"	1605.0	241000	6.0	0.600
13	17.5	"	2380.0	274500	7.8	0.780
14	22.7	"	3086.0	309000	8.7	0.870
15	28.0	"	3810.0	343500	9.3	0.930

TABLE- 44

Run No.LSP/D/d_{p_3}/h_{s_3}/R_4 Average fluid temp.= 28°C.

1	2		3	4	5	6
1	5.7	CCl_4	93.0	5925	-	-
2	11.8	"	192.1	9875	-	-
3	12.0	"	195.7	15800	-	-
4	11.8	"	192.1	21720	-	-
5	12.5	"	204.1	37550	-	-
6	12.7	"	207.0	49400	-	-
7	13.1	"	213.5	71100	-	-
8	13.9	"	226.5	104800	-	-
9	14.6	"	238.0	138200	-	-
10	15.4	"	251.0	173800	-	-
11	23.9	"	390.0	185700	0.5	0.050
12	4.8	Hg.	653.0	207500	2.5	0.250
13	10.1	"	1373.0	241000	5.2	0.520
14	15.5	"	2107.0	274500	7.0	0.700
15	21.2	"	2884.0	309000	8.3	0.830
16	26.7	"	3635.0	343500	9.0	0.900

TABLE- 45

Run No.LSP/D/d_{p3}/h_{s_4}/R_1 Average fluid Temp.=28°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	13.4	CCl_4	218.5	9875	-	-
2	15.3	"	249.5	15800	-	-
3	16.1	"	262.4	21720	-	-
4	16.1	"	262.4	37550	-	-
5	16.7	"	272.0	49400	-	-
6	16.9	"	275.5	71100	-	-
7	17.7	"	288.5	104800	-	-
8	2.2	Hg.	299.0	124300	1.2	0.100
9	3.7	"	503.0	138200	3.0	0.250
10	7.9	"	1075.0	173800	6.0	0.500
11	13.5	"	1835.0	207500	8.4	0.700
12	19.5	"	2650.0	241000	10.0	0.833
13	26.3	"	3580.0	274500	11.0	0.917

TABLE- 46

Run No.LSP/D/d_{p3}/h_{s_4}/R_2 Average fluid temp.=28.5°C

1	2		3	4	5	6
1	8.5	CCl_4	138.5	9875	-	-
2	14.4	"	234.6	15800	-	-
3	14.8	"	241.5	21720	-	-
4	14.8	"	241.5	37550	-	-
5	15.2	"	248.0	49400	-	-
6	15.5	"	252.5	71100	-	-
7	16.4	"	267.5	104800	-	-
8	17.6	"	287.0	138200	-	-
9	2.5	Hg.	340.0	160000	1.2	0.100
10	4.4	"	599.0	173800	2.8	0.233
11	10.0	"	1360.0	207500	6.0	0.500
12	15.9	"	2160.0	241000	8.5	0.708
13	22.1	"	3005.0	274500	10.0	0.833
14	27.8	"	3780.0	309000	10.8	0.900

TABLE- 47

Run No.LSP/D/d_{p_3}/h_{s_4}/R_3 Average fluid temp.=29°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	5.0	CCl_4	81.5	9875	-	-
2	13.9	"	226.5	15800	-	-
3	14.3	"	233.0	21720	-	-
4	15.1	"	246.0	37550	-	-
5	15.3	"	249.5	49400	-	-
6	15.7	"	256.0	71100	-	-
7	16.5	"	269.0	104800	-	-
8	17.3	"	282.0	138200	-	-
9	19.3	"	314.5	167000	-	-
10	3.0	Hg.	408.0	179800	1.2	0.100
11	7.2	"	979.0	207500	4.2	0.350
12	13.0	"	1768.0	241000	7.0	0.583
13	19.5	"	2650.0	274500	9.0	0.750
14	25.6	"	3480.0	309000	10.0	0.833
15	32.5	"	4420.0	343500	11.0	0.917

TABLE- 48

Run No.LSP/D/d_{p_3}/h_{s_4}/R_4 Average fluid temp.= 28.5°C.

1	2		3	4	5	6
1	13.5	CCl_4	220.0	9875	-	-
2	14.7	"	239.5	15800	-	-
3	15.1	"	246.0	37550	-	-
4	15.5	"	252.5	49400	-	-
5	15.9	"	259.2	71100	-	-
6	16.6	"	270.5	104800	-	-
7	18.5	"	302.0	173800	-	-
8	20.5	"	334.0	185700	0.6	0.050
9	4.0	Hg.	544.0	199500	1.8	0.150
10	9.4	"	1278.0	221200	4.5	0.375
11	12.5	"	1700.0	241000	6.0	0.500
12	19.5	"	2650.0	274500	8.4	0.700
13	25.4	"	3455.0	309000	9.6	0.800
14	37.6	"	5105.0	379000	11.0	0.917

T A B L E- 49

Run No.LSP/D/d_{p_4}/h_{s_1}/R_1 Average fluid temp.=22°C

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	5.9 CCl_4	96.1	5925	-	-
2	8.4 "	137.0	9875	-	-
3	8.6 "	140.1	15800	-	-
4	8.8 "	143.4	21720	-	-
5	9.2 "	150.0	37550	-	-
6	9.5 "	155.0	49400	-	-
7	10.2 "	166.0	71100	-	-
8	18.4 "	300.0	90850	1.2	0.200
9	4.1 Hg.	557.0	104800	1.8	0.300
10	5.1 "	694.0	117500	3.0	0.500
11	8.7 "	1182.0	145100	4.4	0.733
12	12.0 "	1630.0	173800	5.0	0.833
13	16.9 "	2300.0	207500	5.5	0.917

T A B L E- 50

Run No.LSP/D/d_{p_4}/h_{s_1}/R_2 Average fluid temp.=23.5°C

1	2	3	4	5	6
1	5.6 CCl_4	91.2	5925	-	-
2	8.5 "	138.5	9875	-	-
3	8.9 "	145.0	15800	-	-
4	9.1 "	148.3	21720	-	-
5	9.5 "	155.0	37550	-	-
6	9.7 "	158.0	49400	-	-
7	10.3 "	168.0	71100	-	-
8	11.1 "	181.0	90850	-	-
9	1.6 Hg.	217.5	104800	0.9	0.150
10	4.0 "	544.0	124300	2.4	0.400
11	6.7 "	911.0	145100	3.6	0.600
12	10.8 "	1470.0	173800	4.5	0.750
13	20.0 "	2720.0	241000	5.7	0.950

T A B L E- 51

Run No.LSP/D/d_{p_4}/h_{s_1}/R_3 Average fluid temp.=25.5°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	6.3 CCl_4	102.7	5925	-	-
2	7.5 "	122.2	9875	-	-
3	7.5 "	122.2	15800	-	-
4	7.7 "	125.4	21720	-	-
5	8.1 "	132.0	37550	-	-
6	8.5 "	138.5	49400	-	-
7	9.2 "	150.0	71100	-	-
8	10.7 "	174.5	104800	-	-
9	2.4 Hg.	326.0	124300	1.0	0.166
10	5.1 "	694.0	145100	2.5	0.416
11	9.6 "	1305.0	173800	4.0	0.666
12	14.7 "	2000.0	207500	5.0	0.833
13	24.8 "	3370.0	274500	5.7	0.950

T A B L E- 52

Run No.LSP/D/d_{p_4}/h_{s_1}/R_4 Average fluid temp.=26.5°C

1	2	3	4	5	6
1	6.4 CCl_4	104.2	5925	-	-
2	7.2 "	117.2	9875	-	-
3	7.4 "	120.7	15800	-	-
4	7.5 "	122.2	21720	-	-
5	7.8 "	127.0	37550	-	-
6	8.2 "	133.7	49400	-	-
7	8.6 "	140.0	71100	-	-
8	9.8 "	159.8	104800	-	-
9	13.4 "	218.5	124300	0.6	0.100
10	3.0 Hg.	408.0	145100	1.5	0.250
11	8.0 "	1088.0	173800	3.3	0.550
12	13.3 "	1810.0	207500	4.5	0.750
13	18.3 "	2485.0	241000	5.2	0.866

TABLE- 53

Run No.LSP/D/d_{p_4}/h_{s_2}/R_1 Average fluid temp.=28°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pe} Cms.	$\frac{h_{pe}}{h_s}$
1	2		3	4	5	6
1	9.0	CCl_4	146.7	5925	-	-
2	9.7	"	158.0	9875	-	-
3	9.9	"	161.2	15800	-	-
4	10.1	"	164.7	21720	-	-
5	10.3	"	168.0	37550	-	-
6	10.7	"	174.3	49400	-	-
7	11.3	"	184.1	71100	-	-
8	15.2	"	248.0	85000	-	-
9	2.5	Hg.	340.0	96800	2.0	0.250
10	5.2	"	706.0	117500	3.6	0.450
11	8.1	"	1101.0	138200	5.0	0.625
12	13.4	"	1820.0	173800	6.3	0.787
13	21.6	"	2940.0	207500	7.5	0.937

TABLE- 54

Run No.LSP/D/d_{p_4}/h_{s_2}/R_2 Average fluid Temp.=21°C.

1	2		3	4	5	6
1	9.2	CCl_4	150.0	5925	-	-
2	10.0	"	163.0	9875	-	-
3	10.0	"	163.0	15800	-	-
4	10.2	"	166.2	21720	-	-
5	10.6	"	172.8	37550	-	-
6	11.0	"	179.2	49400	-	-
7	11.6	"	189.0	71100	-	-
8	19.1	"	311.5	90850	-	-
9	2.5	Hg.	340.0	104800	1.2	0.150
10	4.3	"	585.0	117500	2.5	0.313
11	10.6	"	1440.0	152000	5.0	0.625
12	14.6	"	1985.0	173800	6.0	0.750
13	20.5	"	2790.0	207500	7.0	0.875
14	27.4	"	3725.0	241000	7.5	0.937

TABLE-55

Run No.LSP/D/d_{p_4}/h_{s_2}/R_3 Average fluid temp.= 22^{o}C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	9.0	CCl_4	146.8	5925	-	-
2	9.4	"	153.1	9875	-	-
3	9.6	"	156.3	15800	-	-
4	9.8	"	159.8	21720	-	-
5	10.0	"	163.0	37550	-	-
6	10.4	"	169.5	49400	-	-
7	11.2	"	182.7	71100	-	-
8	12.6	"	205.5	104800	-	-
9	1.9	Hg.	258.5	117500	0.8	0.100
10	5.6	"	761.0	138200	2.8	0.350
11	12.1	"	1647.0	173800	5.0	0.625
12	18.9	"	2585.0	207500	6.8	0.850
13	26.8	"	3645.0	248000	7.5	0.937

TABLE-56

Run No.LSP/D/d_{p_4}/h_{s_2}/R_3 Average fluid temp.=23.5^{o}C.

1	2		3	4	5	6
1	7.8	CCl_4	127.0	5925	-	-
2	9.3	"	151.4	9875	-	-
3	9.5	"	155.0	15800	-	-
4	9.7	"	158.0	21720	-	-
5	10.2	"	166.2	37550	-	-
6	10.6	"	173.0	49400	-	-
7	11.2	"	182.7	71100	-	-
8	12.4	"	202.0	104800	-	-
9	13.8	"	224.6	124300	-	-
10	2.6	Hg.	354.0	138200	1.0	0.125
11	5.3	"	721.0	152000	2.5	0.313
12	9.3	"	1265.0	173800	4.0	0.500
13	16.4	"	2235.0	207500	6.0	0.750
14	23.8	"	3240.0	241000	7.0	0.875
15	29.2	.	3975.0	274500	7.6	0.950

TABLE - 57

Run No. $LSP/D/d_{p_4}/h_{s_3}/R_1$ Average fluid temp.= 25.5°C

Sl. No.	ΔH Cms.	ΔP_T Kg./m^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	8.5 CCl_4	138.6	5925	-	-
2	11.9 "	194.0	9875	-	-
3	12.1 "	197.1	15800	-	-
4	12.3 "	200.5	21720	-	-
5	12.7 "	207.0	37550	-	-
6	12.9 "	210.0	49400	-	-
7	13.3 "	216.5	71100	-	-
8	2.3 Hg.	312.5	90850	1.5	0.150
9	4.0 "	544.0	104800	3.2	0.320
10	6.2 "	843.0	117500	4.5	0.450
11	9.7 "	1320.0	138200	6.2	0.620
12	17.1 "	2325.0	173800	8.0	0.800
13	30.6 "	4160.0	241000	9.2	0.920

TABLE - 58

Run No. $LSP/D/d_{p_4}/h_{s_3}/R_2$ Average fluid temp.= 26.5°C.

1	2	3	4	5	6
1	9.8 CCl_4	160.0	5925	-	-
2	11.8 "	192.2	9875	-	-
3	12.0 "	195.7	15800	-	-
4	12.2 "	199.0	21720	-	-
5	12.8 "	208.5	37550	-	-
6	13.0 "	212.0	49400	-	-
7	13.4 "	218.4	71100	-	-
8	15.0 "	244.4	90850	-	-
9	3.7 Hg.	503.0	117500	2.3	0.230
10	7.0 "	952.0	138200	4.2	0.420
11	9.3 "	1265.0	152000	5.2	0.520
12	14.0 "	1905.0	173800	6.6	0.660
13	21.2 "	2880.0	207500	8.2	0.820
14	35.7 -	4850.0	274500	9.3	0.930

TABLE- 59.

Run No.LSP/D/d_{p_4}/h_{s_3}/R_3 Average fluid temp.= 27.5°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	7.3 CCl_4	119.0	5925	-	-
2	11.5 "	187.4	9875	-	-
3	12.2 "	199.0	15800	-	-
4	12.6 "	205.5	21720	-	-
5	13.0 "	212.0	37550	-	-
6	13.4 "	218.2	49400	-	-
7	13.6 "	221.8	71100	-	-
8	15.3 "	249.5	104800	-	-
9	15.7 "	256.0	117500	-	-
10	2.9 Hg.	394.0	131300	1.3	0.130
11	7.0 "	953.0	152000	3.5	0.350
12	11.3 "	1538.0	173800	5.2	0.520
13	19.5 "	2650.0	207500	7.8	0.780
14	27.2 "	3700.0	241000	8.8	0.880
15	41.4 "	5630.0	309000	9.5	0.950
1	2	3	4	5	6

TABLE- 60.

Run No.LSP/D/d_{p_4}/h_{s_3}/R_4 Average fluid temp.= 28°C

1	2	3	4	5	6
1	6.6 CCl_4	107.4	5925	-	-
2	11.8 "	192.2	9875	-	-
3	12.0 "	195.5	15800	-	-
4	12.7 "	207.0	21720	-	-
5	13.2 "	215.0	37550	-	-
6	13.4 "	218.2	49400	-	-
7	13.6 "	221.8	71100	-	-
8	14.9 "	242.6	104800	-	-
9	17.6 "	286.5	131300	-	-
10	4.2 Hg.	571.0	152000	2.0	0.200
11	8.5 "	1158.0	173800	4.2	0.420
12	16.6 "	2260.0	207500	7.0	0.700
13	23.9 "	3250.0	241000	8.2	0.820
14	31.4 "	5270.0	274500	9.0	0.900
15	39.2 "	5340.0	309000	9.4	0.940

TABLE- 61

Run No.LSP/D/d_{p_4}/h_{s_4}/R_1 Average fluid temp.= 20°C

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	9.3	CCl_4	151.5	5925	-	-
2	15.8	"	257.5	9875	-	-
3	16.0	"	260.5	15800	-	-
4	16.2	"	264.0	21720	-	-
5	16.8	"	274.0	37550	-	-
6	17.2	"	280.0	49400	-	-
7	18.2	"	296.5	71100	-	-
8	2.6	Hg.	354.0	85000	1.8	0.150
9	6.6	"	897.0	104800	5.0	0.419
10	9.1	"	1240.0	117500	6.3	0.525
11	15.6	"	2120.0	138200	8.1	0.675
12	23.2	"	3155.0	173800	10.0	0.833
13	32.5	"	4420.0	207500	11.0	0.917

TABLE- 62.

Run No.LSP/D/d_{p_4}/h_{s_4}/R_2 Average fluid temp.= 21°C

1	2		3	4	5	6
1	9.1	CCl_4	148.3	5925	-	-
2	14.5	"	236.2	9875	-	-
3	14.7	"	239.5	15800	-	-
4	14.9	"	242.6	21720	-	-
5	15.5	"	252.5	37550	-	-
6	15.9	"	259.0	49400	-	-
7	16.6	"	270.5	71100	-	-
8	18.0	"	293.5	90850	-	-
9	2.5	Hg.	340.0	104800	1.2	0.100
10	4.8	"	653.0	117500	3.0	0.250
11	9.4	"	1280.0	138200	5.4	0.450
12	18.5	"	2525.0	173800	8.4	0.700
13	27.1	"	3686.0	207500	10.0	0.833
14	36.4	"	4950.0	241000	11.0	0.917

TABLE No.63

Run No.LSP/D/d_{p_4}/h_{s_4}/R_3 Average fluid temp.=23°C

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	7.5	CCl_4	122.2	5925	-	-
2	13.3	"	216.5	9875	-	-
3	14.6	"	238.0	15800	-	-
4	15.0	"	244.5	21720	-	-
5	15.2	"	248.0	37550	-	-
6	15.6	"	254.0	49400	-	-
7	16.3	"	266.0	71100	-	-
8	18.0	"	293.5	104800	-	-
9	19.4	"	316.0	117500	-	-
10	4.2	Hg.	571.0	131300	2.0	0.166
11	9.4	"	1280.0	152000	4.8	0.400
12	14.9	"	2025.0	173800	7.0	0.583
13	25.7	"	3500.0	207500	9.5	0.800
14	34.9	"	4750.0	241000	10.8	0.900

TABLE- 64

Run No.LSP/D/d_{p_4}/h_{s_4}/R_4 Average fluid temp.=24.5°C

1	2		3	4	5	6.
1	8.0	CCl_4	130.2	5925	-	-
2	13.6	"	221.5	9875	-	-
3	14.8	"	241.0	15800	-	-
4	15.0	"	244.5	21720	-	-
5	15.2	"	248.0	37550	-	-
6	15.6	"	254.0	49400	-	-
7	16.3	"	266.0	71100	-	-
8	17.9	"	292.0	104800	-	-
9	19.2	"	311.5	124300	-	-
10	4.6	Hg.	625.0	145100	2.0	0.166
11	9.9	"	1349.0	167000	4.5	0.375
12	16.1	"	2190.0	185700	7.0	0.583
13	22.3	"	3035.0	207500	8.5	0.708
14	33.1	"	4500.0	241000	10.5	0.875
15	41.4	"	5630.0	274500	11.2	0.933

TABLE- 65

Run No.LSP/D/d_{p_5}/h_{s_1}/R_1 Average fluid temp.= 26°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	1.6 CCl_4	26.1	5925	-	-
2	7.0 "	114.0	9875	-	-
3	7.6 "	124.0	15800	-	-
4	7.8 "	127.1	21720	-	-
5	8.5 "	138.5	29600	-	-
6	9.3 "	151.5	37500	-	-
7	10.5 "	171.0	43450	-	-
8	2.2 Hg.	299.5	56250	1.5	0.250
9	3.9 "	530.0	71100	2.7	0.450
10	6.3 "	856.0	85000	3.6	0.600
11	10.2 "	1388.0	104800	4.5	0.750
12	16.4 "	2230.0	138200	5.7	0.950

TABLE- 66

Run No.LSP/D/d_{p_5}/h_{s_1}/R_2 Average fluid temp.= 27.5°C.

1	2	3	4	5	6
1	5.8 CCl_4	94.5	5925	-	-
2	6.9 "	112.4	9875	-	-
3	7.1 "	115.7	15800	-	-
4	7.8 "	127.0	21720	-	-
5	8.6 "	140.0	37550	-	-
6	10.4 "	169.5	56250	-	-
7	2.0 Hg.	272.0	71100	1.0	0.166
8	4.3 "	585.0	85000	2.4	0.400
9	8.9 "	1210.0	104800	4.0	0.666
10	13.5 "	1835.0	124300	4.8	0.800
11	17.5 "	2380.0	145100	5.5	0.917

TABLE- 67

Run No.LSP/D/d_{p_5}/h_{s_1}/R_3 Average fluid temp.= 27.5°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	7.0 CCl_4	114.2	5925	-	-
2	9.4 "	153.2	9875	-	-
3	9.7 "	158.0	15800	-	-
4	10.2 "	166.2	21720	-	-
5	11.6 "	189.0	29600	-	-
6	12.4 "	202.0	37550	-	-
7	14.1 "	230.0	49400	-	-
8	20.2 "	329.0	71100	-	-
9	3.5 Hg.	475.0	85000	1.2	0.200
10	8.2 Hg.	1115.0	104800	3.0	0.500
11	11.3 "	1537.0	117500	4.0	0.666
12	15.9 "	2160.0	138200	4.8	0.800
13	24.1 "	3280.0	173800	5.7	0.950

TABLE- 68

Run No.LSP/D/d_{p_5}/h_{s_1}/R_4 Average fluid temp.=28.5°C.

1	2	3	4	5	6
1	6.7 CCl_4	109.2	5925	-	-
2	7.7 "	125.5	9875	-	-
3	8.3 "	135.2	15800	-	-
4	9.9 "	161.3	21720	-	-
5	10.4 "	169.5	29600	-	-
6	11.3 "	184.0	37550	-	-
7	12.9 "	210.0	49400	-	-
8	16.4 "	267.5	71100	-	-
9	23.7 "	386.0	85000	-	-
10	4.9 Hg.	665.5	96800	1.75	0.292
11	9.3 "	1264.0	117500	3.30	0.550
12	14.6 "	1985.0	138200	4.50	0.750
13	18.0 "	2445.0	152000	5.10	0.850
14	26.6 "	3620.0	185700	5.70	0.950

TABLE- 69

Run No.LSP/D/d_{p_5}/h_{s_2}/R_1 Average fluid temp.=21°C.

SL. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	8.1	CCl_4	132.0	5925	-	-
2	9.1	"	148.2	9875	-	-
3	9.9	"	161.3	15800	-	-
4	10.9	"	177.5	21720	-	-
5	12.2	"	198.8	29600	-	-
6	13.3	"	216.5	37550	-	-
7	2.3	Hg.	313.0	514000	1.0	0.125
8	4.1	"	558.0	63100	2.4	0.300
9	9.4	"	1280.0	85000	4.8	0.600
10	14.0	"	1905.0	104800	6.0	0.750
11	25.4	"	3460.0	138200	7.2	0.900
12	35.4	"	4810.0	173800	7.6	0.950

TABLE- 70.

Run No.LSP/D/d_{p_5}/h_{s_2}/R_2 Average fluid temp.=22°C.

1	2		3	4	5	6
1	7.1	CCl_4	115.8	5925	-	-
2	9.1	"	148.2	9875	-	-
3	10.1	"	164.5	15800	-	-
4	11.3	"	184.0	21720	-	-
5	12.6	"	205.5	29600	-	-
6	17.2	"	280.0	49400	-	-
7	3.5	Hg.	476.0	71100	1.4	0.175
8	6.8	"	925.0	85000	3.2	0.400
9	10.8	"	1470.0	96800	4.5	0.563
10	17.0	"	2312.0	117500	6.0	0.750
11	23.8	"	3240.0	138200	7.0	0.875
12	33.5	"	4555.0	173800	7.4	0.925

TABLE-71.

Run No.LSP/D/$d_{p_5}/h_{s_2}/R_3$ Average fluid temp.=23°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	7.0	CCl_4	114.0	5925	-	-
2	9.0	"	146.8	9875	-	-
3	9.6	"	156.4	15800	-	-
4	10.4	"	169.5	21720	-	-
5	13.1	"	213.5	37550	-	-
6	15.6	"	254.4	49400	-	-
7	3.0	Hg.	408.0	77000	0.8	0.100
8	6.7	"	911.0	90850	2.5	0.313
9	10.5	"	1480.0	104800	4.0	0.500
10	15.2	"	2066.0	117500	5.0	0.625
11	22.0	"	2995.0	138200	6.6	0.825
12	32.0	"	4350.0	173800	7.2	0.900

TABLE- 72.

Run No.LSP/D/$d_{p_5}/h_{s_2}/R_4$ Average fluid temp.= 25°C.

1	2		3	4	5	6
1.	3.8	CCl_4	62.0	5925	-	-
2	7.7	"	125.5	9875	-	-
3	9.2	"	150.0	15800	-	-
4	9.8	"	159.7	21720	-	-
5	11.3	"	184.2	37550	-	-
6	13.3	"	216.7	49400	-	-
7	20.2	"	329.5	77000	-	-
8	4.0	Hg.	544.0	90850	1.0	0.125
9	8.6	"	1170.0	104800	3.0	0.375
10	13.0	"	1770.0	117500	4.4	0.550
11	19.6	"	2666.0	138200	6.0	0.750
12	23.8	"	3240.0	152000	6.6	0.825
13	30.7	"	4180.0	173800	7.0	0.875

TABLE-73

Run No.LSP/D/d_{p_5}/h_{s_3}/R_1 Average fluid temp.=26.5°C

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	6.0 CCl_4	97.9	5925	-	-
2	11.0 "	179.4	9875	-	-
3	12.0 "	195.8	15800	-	-
4	13.1 "	213.5	21720	-	-
5	14.1 "	230.0	29600	-	-
6	16.9 "	275.5	43450	-	-
7	3.0 Hg.	408.0	56250	2.0	0.200
8	5.3 "	720.0	71100	3.4	0.340
9	10.4 "	1415.0	90850	6.0	0.600
10	15.2 "	2065.0	104800	7.2	0.720
11	19.4 "	2640.0	117500	8.0	0.800
12	25.9 "	3520.0	138200	9.0	0.900
13	35.7 "	4855.0	173800	9.5	0.950

TABLE-74

Run No.LSP/D/d_{p_5}/h_{s_3}/R_2 Average fluid temp.=27.5°C.

1	2	3	4	5	6
1	5.2 CCl_4	84.9	5925	-	-
2	9.7 "	158.0	9875	-	-
3	10.9 "	177.8	15800	-	-
4	11.7 "	191.0	21720	-	-
5	14.0 "	228.2	37550	-	-
6	16.3 "	266.0	49400	-	-
7	18.9 "	308.0	63100	-	-
8	3.7 Hg.	503.0	77000	1.8	0.180
9	7.7 "	1048.0	90850	4.0	0.400
10	13.0 "	1770.0	104800	5.8	0.580
11	17.2 "	2340.0	117500	6.7	0.670
12	24.4 "	3320.0	138200	8.0	0.800
13	35.6 "	4845.0	173800	9.2	0.920

TABLE- 75.

Run No.LSP/D/$d_{p_5}/h_{s_3}/R_3$ Average fluid temp.=30°C.

Sl. No.	Δ H Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	6.7	CCl_4	109.2	5925	-	-
2	10.5	"	171.3	9875	-	-
3	11.3	"	184.2	15800	-	-
4	12.2	"	199.0	21720	-	-
5	13.7	"	223.5	37550	-	-
6	15.8	"	257.6	49400	-	-
7	21.2	"	346.0	71100	-	-
8	23.1	"	376.6	77000	-	-
9	4.9	Hg.	666.0	90850	1.8	0.180
10	9.5	"	1292.0	104800	4.0	0.400
11	14.4	"	1960.0	117500	5.5	0.550
12	21.1	"	2870.0	138200	7.3	0.730
13	28.6	"	3890.0	160000	8.5	0.850
14	33.1	"	4500.0	173800	9.1	0.910

TABLE- 76

Run No.LSP/D/$d_{p_5}/h_{s_3}/R_4$ Average fluid temp.=30.5°C.

1	2		3	4	5	6
1	7.5	CCl_4	122.2	5925	-	-
2	11.0	"	179.3	9875	-	-
3	11.8	"	192.5	15800	-	-
4	12.7	"	207.0	21720	-	-
5	14.0	"	228.4	37550	-	-
6	20.2	"	329.5	71100	-	-
7	27.5	"	449.0	85000	-	-
8	4.4	Hg.	599.0	96800	1.2	0.120
9	9.7	"	1320.0	110600	3.5	0.350
10	15.4	"	2095.0	124300	5.8	0.580
11	20.0	"	2720.0	138200	6.8	0.680
12	27.3	"	3720.0	160000	8.2	0.820
13	33.1	"	4500.0	173800	8.9	0.890

TABLE- 77.

Run No.LSP/D/d_{p_5}/h_{s_4}/R_1 Average fluid temp.= 29.5 °C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	9.2	CCl_4	150.0	5925	-	-
2	13.6	"	221.8	9875	-	-
3	14.0	"	228.0	15800	-	-
4	15.7	"	256.0	21720	-	-
5	16.7	"	272.0	29600	-	-
6	19.0	"	310.0	43450	-	-
7	21.6	"	352.0	49400	-	-
8	3.4	Hg.	462.0	63100	2.0	0.166
9	7.2	"	980.0	77000	4.5	0.375
10	12.4	"	1688.0	90850	7.0	0.583
11.	17.3	"	2355.0	104800	8.4	0.700
12	21.3	"	2900.0	117500	9.3	0.775
13	29.4	"	4000.0	138200	10.6	0.883

TABLE- 78

Run No.LSP/D/d_{p_5}/h_{s_4}/R_1 Average fluid temp.=29.5 °C.

1	2		3	4	5	6
1	6.8	CCl_4	110.8	5925	-	-
2	11.8	"	192.5	9875	-	-
3	13.5	"	220.0	15800	-	-
4	14.7	"	240.0	21720	-	-
5	17.9	"	292.0	37550	-	-
6	21.1	"	344.0	49400	-	-
7	24.3	"	396.0	63100	-	-
8	4.0	Hg.	544.0	77000	1.8	0.150
9	8.4	"	1142.0	90850	4.2	0.350
10	13.5	"	1835.0	104800	6.5	0.542
11	18.1	"	2460.0	117500	8.0	0.666
12	27.1	"	3686.0	13[illegible]200	9.8	0.817
13	38.8	"	5280.0	173800	11.4	0.933

TABLE- 79

Run No.LSP/D/d_{p_5}/h_{s_4}/R_3 Average fluid temp.=31.5°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pe} Cms.	$\frac{h_{pe}}{h_s}$
1	2		3	4	5	6
1	7.6	CCl_4	124.0	5925	-	-
2	12.2	"	199.0	9875	-	-
3	14.7	"	240.0	15800	-	-
4	16.3	"	266.0	21720	-	-
5	19.0	"	310.0	37550	-	-
6	22.3	"	364.0	49400	-	-
7	31.3	"	510.5	77000	-	-
8	4.3	Hg.	585.0	87000	1.2	0.100
9	10.6	"	1442.0	104800	4.5	0.375
10.	16.3	"	2220.0	117500	6.9	0.575
11	25.1	"	3420.0	137200	9.0	0.750
12	38.1	"	5190.0	173800	11.0	0.917

TABLE- 80

Run No.LSP/D/d_{p_5}/h_{s_4}/R_4 Average fluid temp.=31.5°C.

1	2		3	4	5	6
1	7.3	CCl_4	119.0	5925	-	-
2	11.3	"	184.3	9875	-	-
3	13.5	"	220.0	15800	-	-
4	14.7	"	240.0	21720	-	-
5	17.2	"	280.5	37550	-	-
6	25.1	"	410.0	71100	-	-
7	3.5	Hg.	476.0	90850	0.6	0.050
8	8.3	"	1129.0	104800	3.0	0.250
9	13.6	"	1850.0	117500	5.4	0.450
10	22.8	"	3100.0	138200	8.1	0.675
11	29.1	"	3960.0	152000	9.5	0.792
12	38.5	"	5240.0	173800	10.8	0.900

TABLE- 81.

Run No.LSP/Cr./$d_{p_2}/h_{s_1}/R_1$ Average fluid temp.= 26°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	3.9 CCl_4	63.5	21720	-	-
2	6.3 "	102.7	37550	-	-
3	8.8 "	143.5	49400	-	-
4	12.3 "	200.4	71100	-	-
5	14.4 "	234.5	104800	-	-
6	17.5 "	285.0	138200	-	-
7	20.9 "	340.5	173800	-	-
8	28.6 "	466.5	241000	-	-
9	3.8 Hg.	516.5	317000	1.8	0.300
10	5.2 "	707.0	343500	2.4	0.400
11	7.9 "	1075.0	379000	3.6	0.600
12	9.5 "	1291.0	413000	4.4	0.733
13	14.2 "	1930.0	480000	5.7	0.950

TABLE- 82.

Run No.LSP/Cr./$d_{p_2}/h_{s_1}/R_2$ Average fluid temp.=28°C.

1	2	3	4	5	6
1	4.4 CCl_4	71.6	21720	-	-
2	6.4 "	104.2	37550	-	-
3	9.9 "	161.2	49400	-	-
4	13.7 "	223.5	71100	-	-
5	18.4 "	300.0	104800	-	-
6	27.8 "	453.0	173800	-	-
7	4.4 Hg.	599.0	343500	1.0	0.166
8	6.2 "	844.0	379000	2.0	0.333
9	8.0 "	1089.0	413000	3.0	0.500
10	10.1 "	1373.0	446000	4.0	0.666
11	14.8 "	2015.0	514000	5.4	0.900

TABLE- 83.

Run No.LSP/Cr./d_{p_2}/h_{s_1}/R_3 Average fluid temp. = 29°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	5.2 CCl_4	84.7	21720	-	-
2	7.6 "	124.0	37550	-	-
3	9.9 "	161.2	49400	-	-
4	15.9 "	259.0	71100	-	-
5	20.7 "	337.5	104800	-	-
6	29.7 "	484.0	173800	-	-
7	36.2 "	590.0	207500	-	-
8	5.5 Hg.	748.0	393000	1.5	0.250
9	6.5 "	884.0	413000	2.0	0.333
10	8.7 "	1182.0	446000	3.0	0.500
11	10.9 "	1481.0	480000	4.0	0.666
12	16.5 "	2242.0	549000	5.4	0.900

TABLE- 84.

Run No.LSP/Cr./d_{p_2}/h_{s_1}/R_4 Average fluid temp.= 29.5°C.

1	2	3	4	5	6
1	4.9 CCl_4	79.8	21720	-	-
2	6.8 "	110.9	37550	-	-
3	9.0 "	146.8	49400	-	-
4	14.8 "	241.0	71100	-	-
5	20.2 "	329.2	104800	-	-
6	29.9 "	487.0	173800	-	-
7	34.4 "	560.0	207500	-	-
8	4.7 Hg.	640.0	413000	0.9	0.150
9	7.2 "	980.0	446000	1.8	0.300
10	9.4 "	1280.0	460000	2.7	0.450
11	11.4 "	1550.0	514000	3.6	0.600
12	16.8 "	2284.0	582000	5.1	0.850

TABLE- 85.

Run No.LSP/Cr./$d_{p_4}/h_{s_1}/R_1$ Average fluid temp.= 30°C.

Sl. No.	ΔH Cms.		ΔP Kg./M²	G Kg./Hr.M²	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	8.1	CCl_4	132.0	5925	-	-
2	14.0	"	228.0	9875	-	-
3	16.1	"	262.0	15800	-	-
4	17.3	"	282.0	21720	-	-
5	19.0	"	310.0	29600	-	-
6	20.7	"	340.5	37550	-	-
7	25.4	"	414.0	49400	-	-
8	34.0	"	554.0	71100	-	-
9	41.6	"	679.0	85000	-	-
10	5.4	Hg.	802.0	124300	1.8	0.300
11	7.7	"	1048.0	138200	2.7	0.450
12	9.5	"	1291.0	152000	3.3	0.550
13	12.4	"	1687.0	173800	4.0	0.666
14	17.5	"	2380.0	207500	5.0	0.833

TABLE- 86

Run No.LSP/Cr.$d_{p_4}/hs_1/R_2$ Average fluid temp.= 30.5°C

1	2		3	4	5	6
1	5.8	CCl_4	94.5	5925	-	-
2	15.6	"	254.0	9875	-	-
3	18.5	"	301.5	15800	-	-
4	20.6	"	336.0	21720	-	-
5	27.5	"	448.5	37550	-	-
6	32.3	"	526.0	49400	-	-
7	41.7	"	680.0	71100	-	-
8	56.7	"	925.0	90850	-	-
9	7.8	Hg.	1061.0	145100	1.2	0.200
10	9.7	"	1320.0	160000	2.0	0.333
11	12.5	"	1700.0	179800	3.2	0.533
12	16.5	"	2244.0	207500	4.0	0.666
13	22.6	"	3075.0	241000	5.2	0.866

TABLE- 87

Run No.LSP/Cr./d_{p_4}/h_{s_1}/R_3 Average fluid temp.=29°C.

Sl. No.	ΔH Cms.		ΔP Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	7.8	CCl_4	127.1	5925	-	-
2	17.1	"	278.5	9875	-	-
3	18.4	"	300.0	15800	-	-
4	20.3	"	331.0	21720	-	-
5	26.4	"	430.0	37550	-	-
6	33.9	"	552.5	49400	-	-
7	43.5	"	709.0	71100	-	-
8	52.7	"	860.0	85000	-	-
9	59.9	"	975.0	96800	-	-
10	7.9	Hg.	1074.0	152000	0.8	0.133
11	10.7	"	1455.0	173800	1.8	0.300
12	14.1	"	1920.0	193700	3.0	0.500
13	18.1	"	2460.0	214200	3.9	0.650
14	22.9	"	3115.0	241000	5.0	0.833

TABLE- 88

Run No.LSP/Cr.d_{p_4}/h_{s_1}/R_4 Average fluid temp.=30°C.

1	2		3	4	5	6
1	7.2	CCl_4	117.3	5925	-	-
2	18.4	"	300.0	9875	-	-
3	20.9	"	341.0	15800	-	-
4	24.4	"	398.0	21720	-	-
5	29.6	"	482.0	37550	-	-
6	36.0	"	586.0	49400	-	-
7	49.5	"	806.0	71100	-	-
8	7.2	Hg.	980.0	152000	-	-
9	9.4	"	1279.0	167000	0.6	0.100
10	12.0	"	1630.0	185700	1.5	0.250
11	15.9	"	2160.0	207500	2.7	0.450
12	22.4	"	3045.0	241000	4.5	0.750
13	28.8	"	3920.0	274500	5.4	0.900

TABLE- 89.

Run No.LSP/Ba./$d_{p_2}/h_{s_1}/R_1$ Average fluid temp.=26°C.

Sl. No.	ΔH Cms.	ΔP Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	7.7 CCl_4	125.4	21720	-	-
2	12.3 "	200.2	37550	-	-
3	17.5 "	285.0	49400	-	-
4	26.2 "	426.5	71100	-	-
5	30.2 "	492.0	85000	-	-
6	34.1 "	555.0	104800	-	-
7	41.7 "	680.0	138200	-	-
8	5.7 Hg.	775.0	309000	0.9	0.150
9	7.2 "	980.0	343500	1.5	0.250
10	10.2 "	1388.0	379000	2.4	0.400
11	12.9 "	1754.0	413000	3.2	0.533
12.	18.3 "	2490.0	446000	3.9	0.650
13	28.7 "	3904.0	549000	5.1	0.850

TABLE- 90

Run No.LSP/Ba/$d_{p_2}/h_{s_1}/R_2$ Average fluid temp.= 27°C.

1	2	3	4	5	6
1	8.1 CCl_4	132.0	21720	-	-
2	15.8 "	257.5	43450	-	-
3	25.6 "	417.0	71100	-	-
4	30.7 "	500.0	96800	-	-
5	36.8 "	600.0	124300	-	-
6	4.8 Hg.	653.0	336500	-	-
7	7.8 "	1061.0	379000	1.2	0.200
8	10.9 "	1482.0	413000	1.8	0.300
9	14.1 "	1920.0	446000	2.4	0.400
10	17.7 "	2406.0	480000	3.0	0.500
11	21.7 "	2952.0	514000	3.9	0.650
12	29.9 "	4060.0	582000	4.8	0.800

TABLE- 91.

Run No.LSP/Ba/d_{p_2}/h_{s_1}/R_3 Average fluid temp.=29.5°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M²	G Kg./Hr.M²	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	7.8	CCl_4	127.0	21720	-	-
2	13.4	"	218.2	43450	-	-
3	23.0	"	373.0	71100	-	-
4	30.4	"	495.0	104800	-	-
5	38.8	"	632.0	138200	-	-
6	4.8	Hg.	654.0	379000	-	-
7	6.6	"	899.0	413000	0.90	0.150
8	10.9	"	1482.0	454500	1.50	0.250
9	13.9	"	1890.0	480000	2.10	0.350
10	17.6	"	2395.0	514000	2.80	0.467
11	21.4	"	2910.0	549000	3.30	0.550
12	25.2	"	3430.0	582000	4.00	0.666
13	34.6	"	4700.0	651000	5.00	0.833

TABLE- 92.

Run No.LSP/Ba./d_{p_2}/h_{s_1}/R_4 Average fluid temp.=30°C

1	2		3	4	5	6
1	6.7	CCl_4	109.0	21720	-	-
2	15.6	"	254.0	49400	-	-
3	23.9	"	389.5	71100	-	-
4	30.8	"	501.5	104800	-	-
5	34.9	"	569.0	124300	-	-
6	43.7	"	712.0	160000	-	-
7	5.4	Hg.	735.0	379000	-	-
8	6.2	"	844.0	413000	-	-
9	7.2	"	980.0	446000	-	-
10	10.5	"	1430.0	468000	1.20	0.200
11	13.3	"	1810.0	494000	1.80	0.300
12	17.3	"	2355.0	529500	2.40	0.400
13	24.2	"	3295.0	582000	3.60	0.600
14	37.6	"	5110.0	685000	5.10	0.850

TABLE- 93

Run No.LSP/Ba./d_{p_4}/h_{s_1}/R_1 Average fluid temp = 30°C.

Sl. No.	ΔH Cms.		ΔP Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1			2	3	4	5	6
1	2.4	CCl_4	39.1	5925	-	-
2	8.9	"	145.0	9875	-	-
3	19.9	"	324.0	15800	-	-
4	20.9	"	340.5	21720	-	-
5	23.3	"	380.0	29600	-	-
6	23.9	"	390.0	37550	-	-
7	27.3	"	445.0	49400	-	-
8	33.1	"	540.0	71100	-	-
9	40.0	"	652.0	90850	-	-
10	46.8	"	763.0	104800	-	-
11	6.1	Hg.	830.0	145100	1.5	0.250
12	9.5	"	1292.0	160000	2.4	0.400
13	11.3	"	1536.0	173800	3.0	0.500
14	15.6	"	2120.0	193700	3.6	0.600
15	20.6	"	2800.0	221200	4.5	0.750
16	32.2	"	4380.0	274500	5.4	0.900

TABLE- 94.

Run No.LSP/Ba./d_{p_4}/h_{s_1}/R_2 Average fluid temp.= 31°C.

1	2		3	4	5	6
1	5.8	CCl_4	94.5	5925	-	-
2	19.3	"	314.4	9875	-	-
3	21.4	"	348.5	15800	-	-
4	23.2	"	378.0	21720	-	-
5	24.4	"	398.0	29600	-	-
6	29.9	"	487.0	49400	-	-
7	37.2	"	606.0	71100	-	-
8	45.7	"	745.0	90850	-	-
9	51.7	"	844.0	104800	-	-
10	7.2	Hg.	980.0	167000	1.0	0.166
11	10.1	"	1372.0	179800	1.8	0.300
12	14.6	"	1985.0	199500	2.7	0.450
13	19.0	"	2580.0	221200	3.5	0.583
14	23.8	"	3240.0	241000	4.2	0.700
15	31.6	"	4300.0	274500	5.0	0.833

TABLE- 95

Run No.LSP/B_a/d_{p_4}/h_{s_1}/R_3 Average fluid temp.= 29°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	7.8	CCl_4	127.1	5925	-	-
2	19.6	"	319.5	9875	-	-
3	20.5	"	334.0	15800	-	-
4	23.8	"	388.0	21720	-	-
5	26.2	"	427.0	37550	-	-
6	30.7	"	500.0	49400	-	-
7	37.9	"	618.0	71100	-	-
8	55.3	"	901.0	110600	-	-
9	8.4	Hg.	1142.0	185700	1.0	0.166
10	12.9	"	1754.0	207500	2.1	0.350
11	21.2	"	2880.0	241000	3.5	0.585
12	29.4	"	4000.0	274500	4.5	0.750
13	37.5		5100.0	309000	5.1	0.850

TABLE- 96

Run No.LSP/Ba./d_{p_4}/h_{s_1}/R_4 Average fluid temp.=30°C.

1	2		3	4	5	6
1	7.7	CCl_4	125.5	5925	-	-
2	21.8	"	355.0	9875	-	-
3	23.1	"	376.5	15800	-	-
4	26.0	"	424.0	21720	-	-
5	33.6	"	547.0	43450	-	-
6	42.4	"	690.0	71100	-	-
7	5.4	Hg.	735.0	173800	-	-
8	10.2	"	1388.0	207500	0.9	0.150
9	14.7	"	2000.0	228000	1.8	0.300
10	20.7	"	2820.0	248000	3.0	0.500
11	27.3	"	3715.0	274500	3.9	0.650
12	44.7	"	6085.0	343500	5.4	0.900

TABLE- 97

Run No,LSP/I/d_{p2}/h_{s_1}/R_1 Average Fluid Temp.=27°C

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	3.2	CCl_4	52.1	21720	-	-
2	5.5	"	89.6	37550	-	-
3	7.2	"	117.3	49400	-	-
4	10.7	"	174.5	71100	-	-
5	18.8	"	306.5	104800	-	-
6	19.9	"	324.0	138200	-	-
7	20.7	"	338.0	173800	-	-
8	21.6	"	352.0	207500	-	-
9	24.0	"	391.0	274500	-	-
10	26.8	"	437.0	331000	-	-
11	4.9	Hg.	666.0	413000	1.2	0.200
12	7.3	"	980.0	446000	2.0	0.333
13	11.8	"	1605.0	485000	3.0	0.500
14	14.6	"	1985.0	549000	3.9	0.650
15	18.4	"	2500.0	618000	4.5	0.750
16	25.8	"	3505.0	685000	5.0	0.833

TABLE- 98

Run No.LSP/I/d_{p_2}/h_{s_1}/R_2 Average fluid temp.=28.5°C.

1	2		3	4	5	6
1	3.0	CCl_4	48.9	21720	-	-
2	4.8	"	78.2	37550	-	-
3	10.2	"	166.2	71100	-	-
4	18.7	"	304.5	104800	-	-
5	20.8	"	339.0	138200	-	-
6	22.9	"	373.5	207500	-	-
7	25.3	"	412.0	274500	-	-
8	27.9	"	455.0	343500	-	-
9	34.8	"	567.0	413000	-	-
10	44.6	"	727.0	480000	1.5	0.250
11	7.2	Hg.	980.0	514000	2.0	0.333
12	9.4	"	1278.0	549000	2.5	0.416
13	14.6	"	1985.0	618000	3.8	0.633
14	19.5	"	2650.0	685000	4.5	0.750

TABLE- 99

Run No.LSP/I/$d_{p_2}/h_{s_1}/R_3$ Average fluid temp.= 30°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pe} Cms.	$\frac{h_{pe}}{h_s}$
1	2		3	4	5	6
1	2.6	CCl_4	42.4	21720	-	-
2	3.8	"	62.0	37550	-	-
3	8.7	"	142.0	71100	-	-
4	18.2	"	296.5	104800	-	-
5	20.3	"	331.0	138200	-	-
6	23.6	"	384.0	207500	-	-
7	29.0	"	472.5	343500	-	-
8	36.1	"	589.0	480000	-	-
9	6.1	Hg.	830.0	514000	1.3	0.217
10	8.7	"	1182.0	582000	2.4	0.400
11	11.4	"	1550.0	618000	3.0	0.500
12	16.9	"	2300.0	685000	4.0	0.666
13	25.4	"	3460.0	715000	5.1	0.850

TABLE- 100

Run No.LSP/I/$d_{p_2}/h_{s_1}/R_4$ Average fluid temp.=31°C.

1	2		3	4	5	6
1	2.8	CCl_4	45.6	21720	-	-
2	4.8	"	78.2	37550	-	-
3	9.7	"	158.0	71100	-	-
4	18.6	"	303.0	104800	-	-
5	21.8	"	355.5	138200	-	-
6	26.8	"	436.0	207500	-	-
7	35.0	"	570.0	343500	-	-
8	44.6	"	727.0	480000	-	-
9	6.8	Hg.	925.0	569000	1.2	0.200
10	9.8	"	1332.0	618000	2.1	0.350
11	14.8	"	2015.0	685000	3.3	0.550
12	21.1	"	2870.0	711000	4.2	0.700
13	30.7	"	4180.0	778000	5.1	0.850

TABLE- 101

Run No.LSP/I/$d_{p_4}/h_{s_1}/R_1$ Average fluid temp.= 28°C.

Sl. No.	ΔH Cms.	ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6
1	0.2 Hg.	27.2	5925	-	-
2	0.6 "	81.6	9875	-	-
3	0.8 "	108.8	15800	-	-
4	0.9 "	122.2	21720	-	-
5	1.0 "	136.0	29600	-	-
6	1.2 "	163.2	43450	-	-
7	1.5 "	204.0	71100	-	-
8	2.0 "	272.0	104800	-	-
9	2.6 "	354.0	124300	-	-
10	4.8 "	653.0	145100	0.9	0.150
11	6.6 "	897.0	160000	1.5	0.250
12	9.4 "	1280.0	179800	2.5	0.416
13	13.7 "	1864.0	207500	3.6	0.600
14	20.4 "	2775.0	241000	4.5	0.750
15	30.0 "	4080,0	309000	5.5	0.917

TABLE- 102

Run No.LSP/I/$d_{p_4}/h_{s_1}/R_2$ Average fluid temp.=29°C.

1	2	3	4	5	6
1	0.2 Hg.	27.2	5925	-	-
2	0.6 "	81.6	9875	-	-
3	0.8 "	108.8	15800	-	-
4	1.0 "	136.0	21720	-	-
5	1.3 "	177.0	43450	-	-
6	1.8 "	245.0	71100	-	-
7	2.6 "	354.0	104800	-	-
8	3.8 "	516.0	145100	-	-
9	4.2 "	571.0	160000	-	-
10	7.5 "	1020.0	185700	0.9	0.150
11	11.3 "	1538.0	207500	2.0	0.333
12	17.1 "	2325.0	241000	3.3	0.550
13	24.0 "	3265.0	274500	4.5	0.750
14	36.0 "	4900.0	343500	5.6	0.933

TABLE- 103

Run No.LSP/I/d_{p_4}/h_{s_1}/R_3 Average fluid temp.=30°C.

Sl. No.	ΔH Cms.		ΔP_T Kg./M^2	G Kg./Hr.M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4	5	6
1	0.2	Hg.	27.2	5925	-	-
2	0.6	"	81.6	9875	-	-
3	0.8	"	108.8	15800	-	-
4	1.0	"	136.0	21720	-	-
5	1.1	"	149.7	29600	-	-
6	1.4	"	190.3	49400	-	-
7	2.0	"	272.0	71100	-	-
8	3.0	"	408.0	104800	-	-
9	4.0	"	544.0	138200	-	-
10	6.6	"	897.0	193700	-	-
11	10.2	"	1388.0	221200	1.0	0.166
12	15.3	"	2080.0	241000	2.1	0.350
13	22.7	"	3090.0	274500	3.6	0.600
14	29.1	"	3960.0	309000	4.5	0.750
15	45.4	"	6170.0	379000	5.5	0.917

TABLE- 104

Run No.LSP/I/d_{p_4}/h_{s_1}/R_4 Average fluid temp.=30.5°C.

1	2		3	4	5	6
1	0.4	Hg.	54.0	5925	-	-
2	0.8	"	108.8	9875	-	-
3	1.0	"	136.0	15800	-	-
4	1.2	"	158.1	21720	-	-
5	1.4	"	190.3	37550	-	-
6	2.2	"	299.0	71100	-	-
7	3.4	"	462.0	104800	-	-
8	5.8	"	789.0	173800	-	-
9	8.0	"	1088.0	221200	-	-
10	12.0	"	1630.0	248000	1.0	0.166
11	17.2	"	2340.0	274500	2.2	0.367
12	24.9	"	3385.0	309000	3.6	0.600
13	33.4	"	4550.0	344000	4.8	0.800

VARIATION OF EXPANDED BED HEIGHT AND BED POROSITY WITH FLUID MASS VELOCITY

TABLE- 105

Run No.LSE/D/d_{p_1}/h_s/R

w_s = 37.2305 gms. ϵ_{pa} = 0.470

h_s = 5.5 cms. Average fluid temp.=26°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	104800	5.6	1.020	0.480
2	138200	5.7	1.037	0.489
3	173800	6.3	1.146	0.537
4	207500	6.8	1.238	0.571
5	241000	7.4	1.345	0.606
6	274500	7.9	1.437	0.631
7	309000	8.5	1.545	0.656
8	343500	9.0	1.637	0.676
9	379000	9.7	1.762	0.699
10	413000	10.4	1.890	0.719
11	446000	11.0	2.000	0.735
12	480000	11.9	2.162	0.755
13	514000	13.4	2.440	0.783
14	549000	14.9	2.710	0.805
15	582000	16.4	2.980	0.822
16	618000	18.0	3.275	0.838
17	651000	20.3	3.690	0.856
18	685000	22.9	4.160	0.873

TABLE- 106

Run No.LSE/D/d_{p_2}/h_s /R

w_s = 35.9870 gms. ϵ_{p_a} = 0.351

h_s = 5.0 Cms. Average fluid temp =31°C.

Sl. No.	G Kg./Hr.M²	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	49400	5.1	1.020	0.365
2	71100	5.5	1.100	0.410
3	90850	5.9	1.180	0.450
4	110600	6.4	1.280	0.493
5	138200	7.1	1.420	0.544
6	173800	8.2	1.640	0.604
7	207500	9.4	1.880	0.654
8	228000	10.4	2.080	0.688
9	248000	11.4	2.280	0.715
10	274500	12.8	2.560	0.746
11	309000	14.9	2.980	0.782
12	343500	17.8	3.560	0.818
13	379000	20.9	4.180	0.845
14	413000	23.8	4.760	0.864
15	446000	28.0	5.600	0.885
16	480000	32.9	6.580	0.902

TABLE- 107

Run No.LSE/D/d_{p_3}/h_s/R

w_s = 51.831 gms. ϵ_{pa} = 0.310

h_s = 7.6 Cms. Average fluid temp.=26°C.

Sl. No.	G Kg./hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	9875	7.8	1.025	0.327
2	15800	8.0	1.052	0.345
3	21720	8.3	1.091	0.367
4	29600	8.6	1.130	0.390
5	37550	8.9	1.170	0.410
6	49400	9.8	1.289	0.464
7	71100	10.9	1.434	0.519
8	90850	12.9	1.700	0.594
9	110600	15.0	1.975	0.651
10	124300	15.9	2.090	0.670
11	138200	18.1	2.380	0.710
12	160000	21.9	2.880	0.761
13	179800	24.8	3.260	0.788
14	193700	27.4	3.604	0.808
15	207500	31.7	4.170	0.834
16	228000	37.9	4.990	0.862
17	248000	44.9	5.900	0.883

TABLE- 108

Run No. LSE/Dd$_{p_4}$/h_s/R

w_s = 41.7429 gms. ϵ_{pa} = 0.256

h_s = 5.8 Cms. Average fluid temp.=28°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	5925	5.9	1.018	0.269
2	9875	6.6	1.140	0.348
3	15800	6.9	1.190	0.375
4	21720	7.2	1.241	0.401
5	29600	7.7	1.329	0.440
6	37550	8.1	1.398	0.467
7	49400	9.3	1.604	0.536
8	63100	10.1	1.740	0.573
9	77000	11.4	1.965	0.621
10	90850	12.9	2.222	0,665
11	104800	14.9	2.566	0.710
12	117500	17.1	2.945	0.747
13	138200	21.4	3.690	0.798
14	160000	28.9	4.980	0.851
15	179800	34.9	6.010	0.877
16	207500	43.9	7.560	0.902

TABLE - 109.

Run No.LSE/D/d_{p_5}/h_s/R

w_s = 44.8356 gms. ϵ_{pa} = 0.222

h_s = 5.8 Cms. Average fluid temp.= 27°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	5925	7.3	1.073	0.275
2	9875	8.0	1.177	0.339
3	15800	9.0	1.322	0.411
4	21720	9.9	1.455	0.465
5	29600	10.9	1.600	0.514
6	37550	12.4	1.822	0.574
7	49400	14.3	2.100	0.629
8	71100	18.4	2.705	0.712
9	85000	23.4	3.440	0.773
10	96800	28.9	4.250	0.817
11	110600	34.8	5.110	0.848
12	124300	42.9	6.300	0.876
13	138200	51.8	7.610	0.898

TABLE- 110.

Run No.LSE/Cr./d_{p_2}/h_s/R $\qquad \epsilon_{pa} = 0.500$

W_s = 56.9233 gms. $\qquad$ Average fluid temp. =25^{o}C

h_s = 6.6 Cms.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	71100	6.7	1.015	0.507
2	90850	7.1	1.076	0.535
3	110600	7.7	1.167	0.571
4	138200	8.5	1.288	0.611
5	173800	9.4	1.422	0.648
6	207500	10.4	1.575	0.682
7	241000	11.7	1.772	0.717
8	274500	13.0	1.970	0.746
9	309000	14.9	2.260	0.779
10	343500	16.9	2.560	0.804
11	379000	20.0	3.030	0.835
12	413000	22.8	3.450	0.855
13	446000	25.8	3.910	0.872
14	480000	28.9	4.380	0.886
15	514000	32.7	4.950	0.899
16	549000	37.8	5.720	0.912
17	582000	44.2	6.700	0.925

TABLE- 111.

Run No.LSE/B_a/d_{p_2}/h_s/R

w_s = 68.5636 gms. ϵ_{pa} = 0.415

h_s = 5.7 Cms. Average fluid temp.= 30°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	71100	5.8	1.018	0.4250
2	90850	6.1	1.070	0.4530
3	110600	6.4	1.122	0.4785
4	138200	7.0	1.228	0.5230
5	160000	7.4	1.300	0.5490
6	179800	7.9	1.388	0.5780
7	207500	8.4	1.472	0.6020
8	241000	9.2	1.614	0.6370
9	274500	10.3	1.810	0.6760
10	309000	11.4	2.000	0.7075
11	343500	12.9	2.260	0.7410
12	379000	14.3	2.508	0.7665
13	413000	15.9	2.790	0.7905
14	446000	17.8	3.120	0.8128
15	480000	19.9	3.490	0.8320
16	549000	25.0	4.390	0.8665
17	618000	30.8	5.400	0.8918

TABLE- 112

Run No.LSE/I/d_{p_2}/h_s/R ϵ_{pa} = 0.436

w_s = 83.359 gms. Average fluid temp.= 28°C.

h_s = 6.7 Cms.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	110600	6.8	1.015	0.445
2	138200	7.4	1.104	0.490
3	173800	7.9	1.180	0.522
4	207500	8.6	1.283	0.560
5	241000	9.4	1.402	0.598
6	274500	10.2	1.520	0.629
7	309000	11.1	1.660	0.660
8	343500	12.1	1.807	0.688
9	379000	13.0	1.940	0.710
10	413000	13.9	2.075	0.728
11	446000	14.9	2.220	0.746
12	480000	16.9	2.520	0.776
13	514000	18.4	2.740	0.794
14	549000	19.9	2.970	0.810
15	582000	22.4	3.340	0.831
16	618000	24.4	3.640	0.841
17	685000	28.9	4.310	0.869

TABLE- 113

Run No.LSE/C_r./d_{p_4}/h_s/R

w_s = 56.3142 gms. ϵ_{pa} = 0.303

h_s = 7.0 Cms. Average fluid temp.= 29°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	5925	7.2	1.030	0.322
2	9875	7.4	1.058	0.340
3	15800	7.6	1.086	0.358
4	21720	7.9	1.129	0.381
5	29600	8.3	1.187	0.411
6	37550	8.7	1.230	0.433
7	49400	9.4	1.342	0.480
8	71100	10.9	1.558	0.552
9	85000	12.4	1.770	0.606
10	96800	13.7	1.960	0.644
11	110600	15.4	2.200	0.682
12	124300	17.0	2.430	0.713
13	138200	19.4	2.770	0.746
14	160000	22.4	3.200	0.782
15	179800	25.9	3.700	0.812
16	207500	32.9	4.700	0.851
17	241000	43.9	6.260	0.888

TABLE- 114

Run No.LSE/B_a/d_{p_4}/h_s/R

w_s = 52.8686 gms. ϵ_{pa} = 0.316

h_s = 4.5 Cms. Average fluid temp.= 31°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	5925	4.6	1.022	0.331
2	9875	4.7	1.045	0.345
3	15800	4.8	1.067	0.359
4	21720	5.0	1.111	0.385
5	29600	5.2	1.155	0.409
6	37550	5.4	1.200	0.430
7	49400	5.9	1.311	0.478
8	71100	6.7	1.490	0.541
9	90850	7.7	1.710	0.600
10	104800	8.4	1.870	0.634
11	117500	9.2	2.045	0.666
12	138200	10.7	2.376	0.712
13	173800	13.4	2.980	0.770
14	207500	17.9	3.980	0.828
15	241000	23.9	5.310	0.871
16	274500	31.9	7.090	0.903

TABLE- 115

Run No.LSE/I/d_{p_4}/h_s/R

w_s = 53.5285 ϵ_{pa} = 0.304

h_s = 4.8 Cms. Average fluid temp.= 25°C.

Sl. No.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	15800	4.9	1.020	0.318
2	21720	5.1	1.062	0.344
3	29600	5.3	1.104	0.369
4	37550	5.5	1.145	0.391
5	49400	5.7	1.188	0.414
6	71100	6.3	1.312	0.469
7	90850	7.0	1.460	0.523
8	110600	8.1	1.690	0.588
9	138200	9.5	1.980	0.648
10	173800	11.5	2.395	0.709
11	207500	14.9	3.100	0.776
12	241000	18.9	3.940	0.823
13	274500	24.9	5.190	0.865
14	309000	31.9	6.650	0.895

VARIATION OF BED PRESSURE DROP AND PACKED BED FORMATION WITH FLUID MASS VELOCITY.

TABLE-1

Run No.GSP/D/d_{p_1}/h_{s_1}/R_1 Average fluid temp.= 35°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_{r_2} Kg/M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	2.6 CCl_4	1079.1	2.1 CCl_4	14.2	-	-
2	6.3 "	2138.5	4.0 "	26.2	-	-
3	9.8 "	2829.4	5.9 "	43.1	-	-
4	17.9 "	4079.6	9.7 "	71.0	-	-
5	24.7 "	4921.8	12.4 "	84.0	-	-
6	34.1 "	5922.0	15.7 "	104.0	-	-
7	44.1 "	6862.9	18.6 "	115.0	-	-
8	52.4 "	7567.0	23.0 "	152.0	-	-
9	62.7 "	8330.3	30.9 "	244.0	1.0	0.166
10	75.7 "	9277.8	41.8 "	371.0	2.0	0.333
11	13.5 Hg.	11909.8	7.1 Hg.	565.0	3.0	0.500
12	16.3 "	13225.8	10.5 "	809.0	4.0	0.666
13	21.4 "	15397.2	16.2 "	1352.0	5.0	0.833

TABLE-2

Run No.GSP/D/d_{p_1}/h_{s_1}/R_2 Average fluid temp.= 37.5°C.

1	2	3	4	5	6	7
1	2.6 CCl_4	1079.1	2.6 CCl_4	22.4	-	-
2	6.3 "	2138.5	4.9 "	40.9	-	-
3	10.1 "	2928.1	7.2 "	62.3	-	-
4	16.0 "	3816.4	10.6 "	95.0	-	-
5	28.6 "	5356.1	16.7 "	140.0	-	-
6	40.0 "	6487.9	20.1 "	153.0	-	-
7	50.6 "	7382.8	24.4 "	183.0	-	-
8	56.6 "	7863.1	27.1 "	203.5	-	-
9	8.4 Hg.	9146.2	4.7 Hg.	339.0	1.2	0.200
10	11.2 "	10692.5	7.1 "	565.0	2.0	0.333
11	15.8 "	13061.3	12.9 "	1032.0	3.0	0.500
12	20.8 "	15199.8	17.3 "	1523.0	3.6	0.600
13	25.0 "	16779.0	21.8 "	1944.0	4.0	0.666

TABLE-3

Run No.GSP/D/d_{p_1}/h_{s_1}/R_3 Average fluid temp.=33°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	3.3	CCl_4	1289.7	2.9	CCl_4	23.7	-	-
2	5.4	"	1908.2	4.8	"	44.2	-	-
3	7.9	"	2526.7	5.8	"	48.5	-	-
4	11.3	"	3092.6	7.9	"	69.3	-	-
5	21.1	"	4494.1	13.4	"	98.0	-	-
6	29.5	"	5448.2	17.2	"	144.0	-	-
7	44.2	"	6862.9	22.2	"	172.0	-	-
8	55.4	"	7790.7	27.7	"	216.5	-	-
9	63.8	"	8409.2	31.9	"	254.0	-	-
10	73.1	"	9080.4	44.0	"	416.0	0.9	0.150
11	10.3	Hg.	10264.8	6.2	Hg.	475.0	1.5	0.250
12	17.7	"	13883.8	9.3	"	753.0	2.4	0.400
13	25.0	"	16779.0	13.9	"	1215.0	3.0	0.500
14	32.4	"	19279.4	26.1	"	2178.0	3.9	0.650

TABLE-4

Run No.GSP/D/d_{p_1}/h_{s_1}/R_4 Average fluid temp.=35.5°C.

1	2		3	4		5	6	7
1	2.4	CCl_4	921.2	2.5	CCl_4	23.2	-	-
2	7.1	"	2335.9	5.9	"	53.1	-	-
3	12.1	"	3290.0	8.8	"	78.2	-	-
4	21.4	"	4520.5	14.5	"	135.0	-	-
5	29.5	"	5448.2	17.6	"	150.0	-	-
6	43.1	"	6757.7	23.8	"	204.0	-	-
7	53.9	"	7652.5	28.1	"	233.0	-	-
8	67.7	"	8718.5	40.8	"	385.0	-	-
9	11.0	Hg.	10659.6	7.8	Hg.	665.0	1.0	0.166
10	17.7	"	13883.8	12.4	"	1128.0	1.8	0.300
11	24.2	"	16450.0	21.8	"	1990.0	2.4	0.400
12	32.4	"	19279.4	34.0	"	3205.0	3.0	0.500

TABLE-5

Run No.GSP/D/d_{p_2}/h_{s_1}/R_1 Average fluid temp.=33°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_{T_2} Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	1.0	CCl_4	361.9	1.7	CCl_4	17.4	-	-
2	1.9	"	671.2	2.8	"	31.6	-	-
3	3.0	"	1194.4	3.8	"	40.4	-	-
4	4.5	"	1645.0	5.0	"	52.0	-	-
5	9.5	"	2822.8	7.4	"	67.5	-	-
6	11.0	"	3112.3	7.9	"	68.8	-	-
7	14.6	"	3645.3	9.1	"	74.2	-	-
8	17.4	"	4007.2	10.5	"	86.0	-	-
9	23.0	"	4737.6	17.9	"	155.0	1.2	0.200
10	32.2	"	5724.6	23.4	"	236.5	1.8	0.300
11	44.0	"	6843.2	35.3	"	387.0	2.4	0.400
12	52.7	"	7567.0	46.5	"	475.0	3.0	0.500
13	67.7	"	8718.5	67.1	"	813.0	3.6	0.600
14	9.5	Hg.	9738.4	9.6	Hg.	971.0	4.2	0.700
15	16.3	"	13225.8	16.4	"	1610.0	5.2	0,866

TABLE-6

Run No.GSP/D/d_{p_2}/h_{s_1}/R_2 Average fluid temp.=35.5°C.

1	2		3	4		5	6	7
1	1.6	CCl_4	546.1	3.0	CCl_4	36.4	-	-
2	2.7	"	1085.7	4.2	"	48.5	-	-
3	3.1	"	1217.3	4.8	"	56.1	-	-
4	4.1	"	1566.0	5.8	"	66.7	-	-
5	5.4	"	1921.4	7.1	"	81.7	-	-
6	10.2	"	2961.0	8.5	"	82.9	-	-
7	13.1	"	3474.2	9.6	"	87.8	-	-
8	17.8	"	4066.4	11.5	"	100.5	-	-
9	23.0	"	4737.6	20.5	"	186.0	0.8	0.133
10	37.9	"	6283.9	30.4	"	303.0	1.2	0.200
11	56.5	"	7869.7	44.4	"	486.0	2.0	0.333
12	73.3	"	9113.3	65.5	"	764.0	3.0	0.500
13	13.1	Hg.	11745.3	13.6	Hg.	1375.0	3.9	0.650
14	19.1	"	14443.1	21.6	"	2200.0	5.0	0.833

TABLE-7

Run No.GSP/D/$d_{p_2}/h_{s_1}/R_3$ Average fluid temp.=31.5°C

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_f Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	1.5 CCl_4	526.4	2.6 CCl_4	30.0	-	-
2	2.9 "	1118.6	4.1 "	46.3	-	-
3	4.1 "	1546.3	5.3 "	58.9	-	-
4	6.5 "	2204.3	7.5 "	82.1	-	-
5	9.0 "	2730.7	8.3 "	84.7	-	-
6	13.1 "	3474.2	10.0 "	94.5	-	-
7	19.6 "	4290.2	12.5 "	111.5	-	-
8	24.8 "	4921.8	15.2 "	131.0	-	-
9	53.8 "	7632.8	40.1 "	428.0	1.2	0.200
10	68.3 "	8751.4	54.3 "	605.0	2.0	0.333
11	11.9 Hg.	11120.2	12.1 Hg.	1220.0	3.0	0.500
12	17.9 "	13554.8	20.2 "	2095.0	4.0	0.666
13	20.4 "	15035.3	26.4 "	2780.0	4.6	0.766

TABLE-8

Run No.GSP/D/$d_{p_2}/h_{s_1}/R_4$ Average fluid temp.=33.5°C.

1	2	3	4	5	6	7
1	1.0 CCl_4	361.9	2.4 CCl_4	29.0	-	-
2	2.1 "	789 .6	3.8 "	46.2	-	-
3	3.7 "	1447.6	5.7 "	67.0	-	-
4	10.0 "	2895.2	9.4 "	98.5	-	-
5	15.3 "	3750.6	11.6 "	112.0	-	-
6	18.0 "	4099.3	12.6 "	117.5	-	-
7	25.1 "	4974.5	16.1 "	146.5	-	-
8	37.9 "	6283.9	21.6 "	188.0	-	-
9	73.3 "	9106.7	59.1 "	660.0	1.2	0.200
10	12.6 Hg.	11449.2	13.8 Hg.	1428.0	2.0	0.333
11	16.1 "	13160.0	21.0 "	2245.0	3.0	0.500
12	19.7 "	14739.2	29.2 "	3210.0	4.0	0.666

TABLE-9

Run No.GSP/D/$d_{p_2}/h_{s_2}/R_1$ Average fluid temp.=30.5°C.

Sl No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms		ΔP_f Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	1.9	CCl_4	671.2	3.3	CCl_4	39.8	-	-
2	2.8	"	1105.4	4.2	"	48.1	-	-
3	3.8	"	1447.6	5.2	"	58.7	-	-
4	6.2	"	2118.8	7.1	"	77.6	-	-
5	8.1	"	2566.2	7.8	"	80.0	-	-
6	11.6	"	3171.6	8.8	"	82.5	-	-
7	13.5	"	3520.3	9.5	"	85.0	-	-
8	20.5	"	4408.6	17.0	"	179.0	1.2	0.150
9	22.9	"	4711.3	19.8	"	215.5	2.0	0.250
10	30.8	"	5593.0	24.5	"	274.0	2.8	0.350
11	42.0	"	6692.1	36.8	"	450.0	3.6	0.450
12	6.1	Hg.	7501.2	6.9	Hg.	623.0	4.5	0.562
13	9.5	"	9738.4	10.6	"	1102.0	5.6	0.700
14	11.5	"	10889.9	16.4	"	1810.0	6.4	0.800

TABLE-10

Run No.GSP/D/$d_{p_2}/h_{s_2}/R_2$ Average fluid temp.=32.5°C.

1	2		3	4		5	6	7
1	1.7	CCl_4	592.2	2.8	CCl_4	32.4	-	-
2	2.7	"	1085.7	3.9	"	43.4	-	-
3	4.0	"	1513.4	5.1	"	56.1	-	-
4	5.8	"	2039.8	6.6	"	71.2	-	-
5	9.1	"	2763.6	8.2	"	81.8	-	-
6	11.6	"	3171.6	8.8	"	82.5	-	-
7	14.1	"	3586.1	9.8	"	87.3	-	-
8	18.6	"	4158.6	11.6	"	99.0	-	-
9	24.1	"	4862.6	17.0	"	162.0	1.0	0.125
10	30.1	"	5527.2	24.2	"	257.0	2.0	0.250
11	39.1	"	6395.8	34.3	"	392.5	3.0	0.375
12	51.0	"	7415.7	48.8	"	577.0	4.0	0.500
13	9.1	Hg.	9508.1	9.3	Hg.	941.0	4.8	0.600
14	12.3	"	11317.6	14.9	"	1580.0	5.6	0.700
15	18.1	"	14048.3	26.0	"	2900.0	6.4	0.800

TABLE-11

Run No.GSP/D/d_{p_2}/h_{s_2}/R_3 Average fluid temp.= 35°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	1.5	CCl_4	526.4	3.0	CCl_4	36.5	-	-
2	2.9	"	1118.6	4.7	"	56.0	-	-
3	4.3	"	1605.5	6.0	"	69.5	-	-
4	7.1	"	2349.1	8.1	"	87.6	-	-
5	8.8	"	2697.8	8.5	"	88.7	-	-
6	13.0	"	3434.8	9.7	"	89.9	-	-
7	16.8	"	3928.3	10.7	"	90.4	-	-
8	28.6	"	5356.1	18.7	"	173.0	1.0	0.125
9	38.3	"	6316.8	30.8	"	335.0	2.0	0.250
10	59.4	"	8086.8	52.9	"	613.0	3.2	0.400
11	9.3	Hg.	9606.8	9.3	Hg.	935.0	4.0	0.500
12	12.7	"	11515.0	15.5	"	1655.0	4.8	0.600
13	16.7	"	13423.2	23.9	"	2610.0	5.6	0.700
14	23.4	"	16121.0	39.1	"	4370.0	6.4	0.800

TABLE-12

Run No.GSP/D/d_{p_2}/h_{s_2}/R_4 Average fluid temp.=30°C

1	2		3	4		5	6	7
1	2.1	CCl_4	789.6	3.7	CCl_4	44.8	-	-
2	3.3	"	1289.7	5.2	"	62.2	-	-
3	4.3	"	1605.5	6.2	"	72.7	-	-
4	6.2	"	2118.8	8.0	"	92.4	-	-
5	10.8	"	3046.5	9.4	"	94.7	-	-
6	14.9	"	3704.5	10.8	"	100.0	-	-
7	20.8	"	4441.5	12.4	"	103.0	-	-
8	34.7	"	5987.8	25.1	"	253.5	0.8	0.100
9	50.1	"	7356.4	46.5	"	549.0	2.2	0.275
10	9.4	Hg.	9620.0	7.9	Hg.	745.0	3.2	0.400
11	12.3	"	11317.6	12.8	"	1295.0	4.0	0.500
12	17.8	"	13916.7	22.7	"	2400.0	5.2	0.650
13	23.8	"	16285.5	34.6	"	3750.0	6.0	0.750

TABLE-13

Run No.GSP/D/d_{p_2}/h_{s_3}/R_1 Average fluid temp.=31°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	2.0	CCl_4	756.7	4.6	CCl_4	59.6	-	-
2	3.6	"	1381.8	6.7	"	79.0	-	-
3	5.2	"	1908.2	8.6	"	106.2	-	-
4	6.9	"	2303.0	9.9	"	119.3	-	-
5	10.6	"	3000.5	10.9	"	120.6	-	-
6	13.2	"	3487.4	11.8	"	122.4	-	-
7	20.0	"	4342.8	22.4	"	270.5	2.0	0.200
8	30.1	"	5527.2	30.0	"	374.0	3.5	0.350
9	44.9	"	6922.2	49.7	"	643.0	5.0	0.500
10	58.0	"	7975.0	65.3	"	865.0	6.0	0.600
11	8.1	Hg.	8883.0	11.4	Hg.	1262.0	6.7	0.670
12	11.2	"	10692.5	17.4	"	1965.0	7.5	0.750
13	13.8	"	12041.4	27.8	"	3160.0	8.0	0.800

TABLE-14

Run No.GSP/D/d_{p_2}/h_{s_3}/R_2 Average fluid temp.=31.5°C.

1	2		3	4		5	6	7
1	1.4	CCl_4	493.5	3.8	CCl_4	50.0	-	-
2	2.8	"	1105.4	5.8	"	74.1	-	-
3	4.4	"	1322.6	8.2	"	109.8	-	-
4	6.2	"	2118.8	9.6	"	118.3	-	-
5	7.8	"	2500.4	10.1	"	118.7	-	-
6	14.4	"	3619.0	12.3	"	127.9	-	-
7	18.8	"	4191.5	17.0	"	186.0	-	-
8	22.2	"	4625.7	22.0	"	253.5	1.2	0.120
9	26.3	"	5106.1	29.5	"	357.5	2.5	0.250
10	32.8	"	5783.8	40.1	"	507.0	3.5	0.350
11	46.2	"	7040.6	62.8	"	824.0	4.2	0.420
12	7.6	Hg.	8554.0	9.1	Hg.	964.0	5.0	0.500
13	11.4	"	10791.2	16.5	"	1837.0	5.8	0.580
14	15.4	"	12831.0	24.3	"	2725.0	6.8	0.680
15	19.6	"	14706.3	34.5	"	3935.0	7.8	0.780

TABLE-15

Run No.GSP/D/d_{p_2}/h_{s_3}/R_3 Average fluid temp.= 32°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	1.1	CCl_4	427.7	3.8	CCl_4	50.8	-	-
2	3.3	"	1289.7	7.7	"	102.9	-	-
3	5.3	"	1888.5	9.8	"	126.1	-	-
4	7.2	"	2368.8	10.5	"	127.5	-	-
5	12.2	"	3303.2	12.7	"	142.0	-	-
6	15.7	"	3763.8	14.1	"	152.0	-	-
7	19.6	"	4296.7	17.9	"	199.0	-	-
8	23.8	"	4803.4	23.4	"	270.5	1.0	0.100
9	30.3	"	5527.2	37.1	"	467.0	2.2	0.220
10	42.3	"	6685.3	53.0	"	684.0	3.0	0.300
11	6.6	Hg.	7863.1	8.3	Hg.	892.0	4.0	0.400
12	10.4	"	10231.9	17.9	"	2071.0	5.0	0.500
13	15.0	"	12633.6	24.4	"	2765.0	6.0	0.600
14	19.9	"	14772.1	35.1	"	3995.0	7.0	0.700

TABLE-16

Run No.GSP/D/d_{p_2}/h_{s_3}/R_4 Average fluid temp.=35°C.

1	2		3	4		5	6	7
1	1.8	CCl_4	644.8	5.1	CCl_4	69.4	-	-
2	3.0	"	1184.4	7.1	"	94.0	-	-
3	4.2	"	1592.4	9.1	"	120.1	-	-
4	6.4	"	2191.1	10.5	"	131.3	-	-
5	8.8	"	2697.8	11.3	"	134.2	-	-
6	16.3	"	3849.3	13.7	"	144.5	-	-
7	24.4	"	4875.8	17.3	"	167.0	-	-
8	30.1	"	5527.2	26.3	"	291.0	1.0	0.100
9	33.2	"	5829.9	36.8	"	450.0	2.2	0.220
10	53.7	"	7632.8	58.9	"	733.0	3.0	0.300
11	11.1	Hg.	10659.6	12.9	Hg.	1360.0	4.4	0.440
12	12.9	"	11679.5	16.7	"	1850.0	5.0	0.500
13	17.3	"	13752.2	25.7	"	2830.0	6.0	0.600
14	24.5	"	16581.6	43.1	"	4865.0	7.2	0.720

TABLE-17

Run No.GSP/D/d_{p_2}/h_{s_4}/R_1 Average fluid temp.= 29°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	1.9	CCl_4	671.2	5.1	CCl_4	69.1	-	-
2	2.7	"	1085.7	6.5	"	86.0	-	-
3	3.6	"	1381.8	7.8	"	102.3	-	-
4	5.2	"	1908.2	9.8	"	125.7	-	-
5	6.7	"	2256.9	10.6	"	132.3	-	-
6	9.4	"	2776.8	11.6	"	137.6	-	-
7	12.3	"	3316.3	12.6	"	140.3	-	-
8	17.6	"	4040.1	17.8	"	211.1	1.5	0.125
9	25.9	"	5053.4	23.2	"	293.2	3.0	0.250
10	38.0	"	6297.1	38.4	"	488.5	4.8	0.400
11	48.7	"	7238.0	7.3	Hg.	800.8	6.0	0.500
12	61.0	"	8211.8	8.2	"	923.2	7.0	0.581
13	74.9	"	9212.0	12.3	"	1412.8	8.0	0.666
14	10.9	Hg.	10528.0	21.6	"	2551.6	9.0	0.750

TABLE-18

Run No.GSP/D/d_{p_2}/h_{s_4}/R_2 Average fluid temp.=30°C.

1	2		3	4		4	6	7
1	2.6	CCl_4	1079.1	6.8	CCl_4	90.8	-	-
2	3.7	"	1447.6	8.7	"	115.8	-	-
3	6.0	"	2072.7	10.6	"	135.3	-	-
4	7.7	"	2487.2	11.2	"	137.1	-	-
5	10.8	"	3046.5	12.0	"	137.5	-	-
6	12.0	"	3257.1	12.4	"	138.9	-	-
7	13.6	"	3487.4	13.0	"	141.9	-	-
8	22.1	"	4606.0	24.5	"	293.4	1.5	0.125
9	32.3	"	5711.4	46.4	"	610.3	4.0	0.333
10	5.2	Hg.	6777.4	7.5	Hg.	835.0	5.4	0.450
11	6.0	"	7435.4	8.9	"	994.4	6.0	0.500
12	9.2	"	9541.0	15.2	"	1741.2	7.2	0.600
13	13.2	"	11712.4	23.9	"	2780.4	8.0	0.666

TABLE-19

Run No.GSP/D/d_{p_2}/h_{s_4}/R_3 Average fluid temp.=31°C

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	1.8 CCl_4	658.0	4.4 CCl_4	58.0	-	-
2	3.7 "	1447.6	7.1 "	89.7	-	-
3	5.2 "	1908.2	9.2 "	116.0	-	-
4	7.9 "	2513.6	10.8 "	130.2	-	-
5	10.7 "	3040.0	11.7 "	132.7	-	-
6	13.4 "	3474.2	12.7 "	136.9	-	-
7	19.2 "	4250.7	14.3 "	139.9	-	-
8	24.6 "	4908.7	24.1 "	276.8	1.5	0.125
9	30.3 "	5527.2	38.5 "	489.6	3.0	0.250
10	5.4 Hg.	6909.0	7.3 Hg.	800.8	4.0	0.333
11	8.0 "	8751.4	12.5 "	1420.0	5.4	0.450
12	9.2 "	9541.0	14.7 "	1673.2	6.0	0.500
13	11.6 "	10857.0	22.1 "	2600.6	7.0	0.581

TABLE-20

Run NO.GSP/D/d_{p_2}/h_{s_4}/R_4 Average fluid temp.=32.°C

1						
1	2.0 CCl_4	756.7	7.0 CCl_4	98.9	-	-
2	3.7 "	1447.6	9.7 "	132.1	-	-
3	4.8 "	1710.8	10.0 "	132.7	-	-
4	7.2 "	2368.8	10.8 "	133.1	-	-
5	10.7 "	3040.0	11.9 "	136.0	-	-
6	13.6 "	3487.4	12.7 "	137.0	-	-
7	21.0 "	4474.4	15.1 "	146.1	-	-
8	27.8 "	5254.0	27.0 "	310.1	1.2	0.100
9	32.7 "	5770.7	42.0 "	536.6	2.3	0.192
10	5.8 Hg.	7303.8	8.5 Hg.	946.0	3.6	0.300
11	9.2 "	9541.0	13.3 "	1482.8	4.8	0.400
12	11.0 "	10593.8	17.1 "	1935.6	5.4	0.450
13	13.2 "	11712.4	22.6 "	2603.6	6.0	0.500
14	15.8 "	12995.5	31.0 "	3616.0	7.0	0.581

TABLE-21

Run No.GSP/D/$d_{p_3}/h_{s_1}/R_1$ Average fluid temp.=34.5°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	0.4 CCl_4	131.6	2.2 CCl_4	28.0	-	-
2	0.8 "	230.3	3.9 "	54.8	-	-
3	1.3 "	460.6	4.8 "	66.6	-	-
4	2.2 "	822.5	5.4 "	72.0	-	-
5	3.5 "	1348.9	6.0 "	73.3	-	-
6	4.5 "	1645.0	6.4 "	74.8	-	-
7	5.7 "	1987.2	7.0 "	78.5	-	-
8	9.1 "	2763.6	11.6 "	137.0	0.9	0.150
9	11.5 "	3158.4	17.0 "	215.5	1.8	0.300
10	17.4 "	4000.6	29.9 "	402.0	3.0	0.500
11	28.4 "	5310.1	56.3 "	787.0	3.9	0.650
12	44.8 "	6922.2	10.3 Hg.	1208.0	4.8	0.800
13	73.3 "	9106.7	16.2 "	1896.0	5.4	0.900

TABLE-22

Run No.GSP/D/$d_{p_3}/h_{s_1}/R_2$ Average fluid temp =35°C.

1	2	3	4	5	6	7
1	0.9 CCl_4	296.1	3.3 CCl_4	44.3	-	-
2	1.1 "	427.7	4.1 "	55.7	-	-
3	1.5 "	526.4	5.0 "	69.0	-	-
4	2.6 "	1079.1	5.5 "	69.3	-	-
5	3.1 "	1217.3	5.6 "	69.8	-	-
6	4.3 "	1605.5	6.3 "	74.5	-	-
7	6.5 "	2204.3	7.0 "	76.0	-	-
8	11.7 "	3211.0	12.5 "	141.0	1.0	0.166
9	14.9 "	3704.5	20.3 "	255.0	2.0	0.333
10	25.8 "	5046.9	40.0 "	532.0	3.0	0.500
11	41.1 "	6593.2	76.0 "	1060.0	3.9	0.650
12	62.4 "	8317.1	14.9 Hg.	1743.0	4.5	0.750
13	10.8 Hg.	10363.5	21.6 "	2490.0	5.4	0.900

TABLE-23

Run No.GSP/D/d_{p_3}/h_{s_1}/R_3 Average fluid temp. =34°C.

Sl No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	0.5 CCl_4	164.5	2.9 CCl_4	39.2	-	-
2	1.1 "	427.7	4.4 "	60.4	-	-
3	1.6 "	546.1	4.9 "	67.2	-	-
4	2.8 "	1105.4	5.4 "	67.6	-	-
5	3.9 "	1500.2	5.9 "	69.6	-	-
6	5.2 "	1908.2	6.4 "	71.4	-	-
7	7.7 "	2487.2	7.3 "	73.5	-	-
8	14.9 "	3704.5	15.4 "	170.6	1.0	0.166
9	20.9 "	4461.2	22.4 "	265.0	1.5	0.250
10	29.4 "	5421.9	39.5 "	509.0	2.4	0.400
11	42.4 "	6705.0	59.6 "	789.0	3.0	0.500
12	8.1 Hg.	8883.0	14.4 Hg.	1670.0	4.0	0.666
13	11.5 "	10922.8	23.8 "	2815.0	5.2	0.866

TABLE-24

Run No.GSP/D/d_{p_3}/h_{s_1}/R_4 Average fluid temp. =33°C.

1	2	3	4	5	6	7
1	0.5 CCl_4	164.5	2.5 CCl_4	32.6	-	-
2	0.9 "	296.1	3.4 "	45.9	-	-
3	1.9 "	671.2	5.0 "	67.5	-	-
4	3.0 "	1184.4	5.6 "	67.8	-	-
5	3.8 "	1447.6	5.9 "	69.8	-	-
6	6.4 "	2191.1	6.8 "	71.0	-	-
7	10.6 "	3000.5	7.9 "	73.5	-	-
8	17.9 "	4073.0	9.5 "	78.0	-	-
9	23.0 "	4724.4	23.1 "	254.5	1.2	0.200
10	42.3 "	6685.3	48.4 "	606.0	2.0	0.333
11	6.1 Hg.	7501.2	7.9 Hg.	853.0	3.0	0.500
12	8.7 "	9277.8	14.0 "	1590.0	3.8	0.633
13	11.5 "	10922.8	21.7 "	2545.0	4.8	0.800
14	15.1 "	12699.4	30.2 "	3545.0	5.4	0.900

TABLE-25

Run No.GSP/D/d_{p_4}/h_{s_1}/R_1 Average fluid temp.= 34°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	0.4 CCl_4	131.6	3.1 CCl_4	42.6	-	-
2	0.5 "	164.5	3.9 "	55.4	-	-
3	1.2 "	460.6	4.8 "	66.7	-	-
4	1.9 "	671.2	5.2 "	70.7	-	-
5	2.3 "	855.4	5.4 "	71.4	-	-
6	3.6 "	1381.8	6.0 "	72.8	-	-
7	5.2 "	1908.2	12.4 "	168.0	1.5	0.250
8	6.8 "	2289.8	18.1 "	254.0	2.4	0.400
9	8.6 "	2900.0	26.6 "	385.0	3.0	0.500
10	14.5 "	3619.0	42.4 "	617.5	4.0	0.666
11	23.0 "	4724.4	66.9 "	982.0	4.5	0.750
12	31.3 "	5632.5	10.0 Hg.	1220.0	5.1	0.850
13	42.3 "	6685.3	14.8 "	1815.0	5.4	0.900

TABLE-26.

Run No.GSP/D/d_{p_4}/h_{s_1}/R_2 Average fluid temp.= 35.5°C

1	2	3	4	5	6	7
1	0.3 CCl_4	98.7	2.7 CCl_4	35.4	-	-
2	0.6 "	184.2	4.2 "	60.2	-	-
3	0.9 "	296.1	4.8 "	68.6	-	-
4	1.6 "	546.1	5.2 "	72.2	-	-
5	2.3 "	855.4	5.6 "	74.6	-	-
6	3.0 "	1184.4	6.0 "	75.8	-	-
7	3.9 "	1500.2	6.4 "	77.6	-	-
8	4.9 "	1743.7	9.5 "	124.1	0.6	0.100
9	6.6 "	1974.0	12.8 "	173.5	1.2	0.200
10	9.6 "	2836.0	22.5 "	313.5	2.0	0.333
11	14.8 "	3684.8	38.9 "	559.0	3.0	0.500
12	20.9 "	4461.2	63.0 "	928.0	3.7	0.616
13	29.1 "	5408.8	8.4 Hg.	1006.0	4.2	0.700
14	40.3 "	6514.2	13.5 "	1663.0	4.8	0.800
15	50.6 "	7382.8	19.3 "	2390.0	5.3	0.883

TABLE-27

Run No.GSP/D/d_{p_4}/h_{s_1}/R_3 Average fluid temp.=32°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	0.3 CCl_4	98.7	2.9 CCl_4	39.7	-	-
2	0.5 "	164.5	4.5 "	65.2	-	-
3	0.9 "	296.1	4.9 "	70.4	-	-
4	2.1 "	789.6	5.5 "	74.0	-	-
5	3.0 "	1184.4	5.9 "	74.1	-	-
6	3.9 "	1500.2	6.3 "	76.2	-	-
7	5.3 "	1888.5	7.1 "	82.2	-	-
8	9.1 "	2763.6	12.6 "	153.0	1.0	0.166
9	14.1 "	3586.1	27.3 "	372.5	2.1	0.350
10	20.4 "	4395.4	47.2 "	672.0	3.0	0.500
11	28.2 "	5303.5	77.8 "	1138.0	3.6	0.600
12	46.0 "	7020.9	14.6 Hg.	1787.0	4.2	0.700
13	57.7 "	7961.8	19.2 "	2370.0	5.0	0.833

TABLE-28

Run No.GSP/D/d_{p_4}/h_{s_1}/R_4 Average fluid temp.=34°C.

1	2	3	4	5	6	7
1	0.1 CCl_4	32.9	1.6 CCl_4	19.0	-	-
2	0.3 "	98.7	2.6 "	34.8	-	-
3	0.5 "	164.5	3.6 "	50.5	-	-
4	0.9 "	296.1	5.0 "	72.0	-	-
5	1.6 "	546.1	5.2 "	72.2	-	-
6	3.1 "	1217.3	6.2 "	79.0	-	-
7	5.4 "	1921.4	7.6 "	90.0	-	-
8	7.4 "	2408.3	8.8 "	99.2	-	-
9	11.1 "	3125.5	27.2 "	368.5	1.0	0.166
10	20.4 "	4395.4	43.8 "	616.0	2.0	0.333
11	28.0 "	5296.9	71.0 "	1028.0	3.0	0.500
12	39.3 "	6415.5	13.7 Hg.	1700.0	3.6	0.600
13	59.5 "	8086.8	21.0 "	2613.0	4.5	0.750

TABLE- 29

Run No.GSP/Cr./$d_{p_2}/h_{s_1}/R_1$ Average fluid temp.= 33°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_{T_2} Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	1.4	CCl_4	493.5	2.1	CCl_4	22.2	-	-
2	2.7	"	1085.7	3.3	"	33.6	-	-
3	4.0	"	1513.4	4.3	"	43.1	-	-
4	5.9	"	2072.7	5.7	"	55.5	-	-
5	9.2	"	2776.8	8.1	"	80.0	-	-
6	13.8	"	3553.2	10.3	"	97.0	-	-
7	20.5	"	4408.6	12.0	"	98.0	-	-
8	30.9	"	5593.0	19.4	"	200.5	1.0	0.166
9	39.9	"	6461.8	29.4	"	310.0	1.8	0.300
10	56.3	"	7856.5	51.2	"	613.0	3.0	0.500
11	9.5	Hg.	9738.4	9.2	Hg.	914.0	4.5	0.750
12	16.4	"	13291.6	16.7	"	1645.0	5.1	0.850

TABLE- 30

Run No.GSP/Cr./$d_{p_2}/h_{s_1}/R_2$ Average fluid temp.= 34°C.

1	2		3	4		5	6	7
1	1.9	CCl_4	671.2	3.1	CCl_4	36.5	-	-
2	3.0	"	1184.4	4.2	"	47.0	-	-
3	5.5	"	1974.0	6.5	"	71.0	-	-
4	7.8	"	2500.4	8.4	"	91.5	-	-
5	12.3	"	3316.3	10.4	"	104.0	-	-
6	19.3	"	4263.8	12.8	"	116.5	-	-
7	26.9	"	5165.3	15.8	"	131.6	-	-
8	31.1	"	5619.3	17.9	"	150.0	-	-
9	38.0	"	6297.1	25.1	"	245.5	1.2	0.200
10	43.5	"	6797.1	30.1	"	306.5	1.5	0.250
11	63.5	"	8396.1	47.9	"	510.0	2.5	0.417
12	9.0	Hg.	9442.3	6.9	Hg.	623.0	3.0	0.500
13	12.3	"	11350.5	10.4	"	969.0	3.6	0.600
14	19.5	"	14673.4	20.5	"	2033.0	4.8	0.800

TABLE-31

Run No.GSP/Cr./$d_{p_2}/h_{s_1}/R_3$ Average fluid temp.= 36.5°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	1.7 CCl_4	592.2	2.8 CCl_4	32.4	-	-
2	3.3 "	1269.9	4.5 "	50.8	-	-
3	5.3 "	1888.5	6.3 "	69.3	-	-
4	8.8 "	2697.8	9.2 "	100.0	-	-
5	15.2 "	3737.4	11.3 "	107.0	-	-
6	20.8 "	4441.5	13.4 "	119.4	-	-
7	28.0 "	5296.9	17.0 "	146.0	-	-
8	46.2 "	7040.6	30.4 "	306.5	1.10	0.183
9	57.5 "	7948.6	38.4 "	385.0	1.50	0.250
10	73.1 "	9080.4	53.0 "	564.0	2.40	0.400
11	12.5 Hg.	11416.3	10.2 Hg.	941.0	3.00	0.500
12	18.3 "	14147.0	18.4 "	1800.0	4.00	0.666
13	22.8 "	15923.6	25.8 "	2605.0	4.50	0.750

TABLE-32

Run No.GSP/Cr./$d_{p_2}/h_{s_1}/R_4$ Average fluid temp.=35°C

1	2	3	4	5	6	7
1	2.4 CCl_4	921.2	3.7 CCl_4	42.7	-	-
2	4.0 "	1513.4	5.5 "	62.6	-	-
3	6.1 "	2105.6	7.4 "	82.8	-	-
4	9.0 "	2730.7	9.7 "	107.6	-	-
5	13.5 "	3520.3	11.0 "	109.4	-	-
6	20.7 "	4441.5	14.0 "	129.2	-	-
7	30.6 "	5553.5	17.6 "	147.0	-	-
8	38.7 "	6362.9	22.0 "	191.4	-	-
9	53.4 "	7626.2	30.2 "	266.0	-	-
10	63.3 "	8389.5	42.0 "	420.0	1.0	0.166
11	72.1 "	9027.8	49.5 "	508.0	1.5	0.250
12	12.5 Hg.	11416.3	9.1 Hg.	790.0	2.4	0.400
13	16.3 "	13225.8	14.4 "	1343.0	3.0	0.500
14	20.1 "	14837.9	20.1 "	1960.0	3.6	0.600
15	27.1 "	17535.7	34.8 "	3620.0	4.5	0.750

TABLE-33

Run No.GSP/Ba./$d_{p_2}/h_{s_1}/R_1$ Average fluid temp.=31°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	1.5 CCl_4	526.4	2.5 CCl_4	28.4	-	-
2	3.1 "	1217.3	4.2 "	46.5	-	-
3	4.9 "	1809.5	5.8 "	62.5	-	-
4	8.1 "	2566.2	8.6 "	92.6	-	-
5	11.7 "	3211.0	11.3 "	121.0	-	-
6	14.5 "	3632.2	12.1 "	124.2	-	-
7	17.7 "	4040.1	13.4 "	133.4	-	-
8	22.5 "	4671.8	15.4 "	144.0	-	-
9	34.1 "	5922.0	30.6 "	347.0	1.2	0.200
10	38.1 "	6303.6	37.1 "	438.0	1.5	0.250
11	51.8 "	7501.2	57.1 "	711.0	2.7	0.450
12	58.0 "	7981.5	59.2 "	782.0	3.0	0.500
13	11.4 Hg.	10857.0	13.4 Hg.	1417.0	4.2	0.700
14	15.8 "	13061.3	22.4 "	2445.0	4.8	0.800

TABLE-34

Run No.GSP/Ba./$d_{p_2}/h_{s_1}/R_2$ Average fluid temp.=32°C.

1	2	3	4	5	6	7
1	1.5 CCl_4	526.4	3.5 CCl_4	44.6	-	-
2	3.4 "	1322.6	5.8 "	70.5	-	-
3	5.6 "	1974.0	8.4 "	102.0	-	-
4	8.4 "	2618.8	11.3 "	135.6	-	-
5	12.0 "	3257.1	12.5 "	141.0	-	-
6	16.8 "	3921.7	14.6 "	156.0	-	-
7	21.1 "	4494.1	16.9 "	173.6	-	-
8	25.9 "	5053.4	19.8 "	201.0	-	-
9	35.2 "	6027.3	30.1 "	334.5	-	-
10	48.7 "	7238.0	55.1 "	694.0	1.5	0.250
11	61.0 "	8211.8	78.5 "	1023.0	2.4	0.400
12	10.0 Hg.	10034.5	13.2 Hg.	1443.0	3.0	0.500
13	16.4 "	13291.6	16.4 "	1605.0	3.9	0.650
14	20.3 "	14969.5	24.7 "	2560.0	4.5	0.750

TABLE-35

Run No.GSP/Ba./$d_{p_2}/h_{s_1}/R_3$ Average fluid temp.=33.5°C.

Sl. No.	ΔH_1 Cms.	G Kg./Hr.M^2	ΔH_2 Cms.	ΔP Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2	3	4	5	6	7
1	2.1 CCl_4	789.6	2.9 CCl_4	31.7	-	-
2	3.8 "	1447.6	4.3 "	44.1	-	-
3	6.4 "	2191.1	6.5 "	66.0	-	-
4	10.3 "	2980.7	9.0 "	90.3	-	-
5	14.2 "	3605.8	10.2 "	93.2	-	-
6	23.6 "	4796.8	13.0 "	100.8	-	-
7	30.2 "	5527.2	15.2 "	109.8	-	-
8	42.7 "	6718.2	22.3 "	182.0	-	-
9	54.1 "	7685.4	42.3 "	455.0	1.2	0.200
10	71.5 "	8975.1	59.2 "	787.0	1.8	0.300
11	10.2 Hg.	10199.0	11.8 Hg.	1240.0	2.4	0.400
12	13.0 "	11712.4	16.9 "	1825.0	3.0	0.500
13	16.8 "	13489.0	22.8 "	2450.0	3.6	0.600
14	22.8 "	15923.6	31.8 "	3415.0	4.2	0.700

TABLE-36

Run No.GSP/Ba./$d_{p_2}/h_{s_1}/R_4$ Average fluid temp.=35.5°C.

1	2	3	4	5	6	7
1	1.7 CCl_4	592.2	2.8 CCl_4	32.4	-	-
2	4.1 "	1546.3	4.9 "	52.4	-	-
3	6.7 "	2256.9	7.2 "	76.2	-	-
4	12.9 "	3421.6	10.6 "	104.0	-	-
5	21.2 "	4494.1	13.2 "	113.0	-	-
6	29.6 "	5461.4	16.0 "	124.6	-	-
7	50.6 "	7382.8	32.5 "	315.0	-	-
8	64.2 "	9100.1	50.4 "	700.0	1.2	0.200
9	74.9 "	9212.0	75.6 "	926.0	1.5	0.250
10	13.8 Hg.	12041.4	15.4 Hg.	1599.0	2.4	0.400
11	19.0 "	14443.1	26.6 "	2875.0	3.0	0.500
12	24.1 "	16450.0	38.2 "	4225.0	3.6	0.600

TABLE-37

Run No.GSP/I/$d_{p_2}/h_{s_1}/R_1$ Average fluid temp.=31°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	3.1	CCl_4	1217.3	3.0	CCl_4	26.9	-	-
2	5.6	"	1974.0	4.9	"	44.9	-	-
3	8.1	"	2566.2	6.5	"	58.5	-	-
4	12.8	"	3408.4	9.3	"	83.6	-	-
5	20.0	"	4342.8	12.1	"	102.2	-	-
6	28.2	"	5303.5	14.4	"	104.7	-	-
7	35.6	"	6053.6	16.1	"	106.3	-	-
8	44.9	"	6922.2	23.2	"	188.2	1.2	0.200
9	58.0	"	7975.0	50.4	"	581.0	2.4	0.400
10	7.6	Hg.	8554.0	9.4	Hg.	980.4	3.0	0.500
11	12.7	"	11515.0	13.5	"	1381.0	4.2	0.700
12	17.0	"	13554.8	20.0	"	2070.0	5.0	0.833

TABLE-38

Run No.GSP/I/$d_{p_2}/h_{s_1}/R_2$ Average fluid temp.=32.5°C.

1	2		3	4		5	6	7
1	2.2	CCl_4	822.5	2.6	CCl_4	26.4	-	-
2	4.4	"	1322.6	4.3	"	46.1	-	-
3	7.7	"	2487.2	6.6	"	62.0	-	-
4	11.9	"	3243.9	9.1	"	84.8	-	-
5	18.4	"	4145.4	11.9	"	104.0	-	-
6	25.0	"	4948.2	13.7	"	107.5	-	-
7	33.7	"	5889.1	16.1	"	110.3	-	-
8	42.5	"	6711.6	18.0	"	111.5	-	-
9	50.7	"	7389.3	27.0	"	225.0	1.2	0.200
10	72.0	"	9014.6	55.1	"	599.0	2.4	0.400
11	10.8	Hg.	10363.5	10.1	Hg.	997.6	3.0	0.500
12	17.1	"	13653.5	13.5	"	1180.0	3.9	0.650
13	22.1	"	15660.4	19.9	"	1821.0	4.5	0.750

TABLE-39

Run No.GSP/I/d_{p_2}/h_{s_1}/R_3 Average fluid temp.= 32.5°C.

Sl. No.	ΔH_1 Cms.		G Kg./Hr.M^2	ΔH_2 Cms.		ΔP_T Kg./M^2	h_{pa} Cms.	$\frac{h_{pa}}{h_s}$
1	2		3	4		5	6	7
1	2.9	CCl_4	1151.5	3.3	CCl_4	32.8	-	-
2	6.2	"	2118.8	5.9	"	57.9	-	-
3	8.9	"	2730.7	7.7	"	74.9	-	-
4	13.1	"	3474.2	10.4	"	99.7	-	-
5	18.3	"	4138.8	12.0	"	105.0	-	-
6	30.8	"	5593.0	15.2	"	107.6	-	-
7	37.5	"	6244.4	16.7	"	109.1	-	-
8	50.0	"	7336.7	19.8	"	111.0	-	-
9	61.0	"	8211.8	30.4	"	240.0	1.0	0.166
10	76.3	"	9317.3	47.9	"	464.0	1.5	0.250
11	12.1	Hg.	11186.0	9.4	Hg.	843.4	2.4	0.400
12	18.3	"	14147.0	16.0	"	1476.0	3.0	0.500
13	22.7	"	15890.7	22.0	"	2082.0	3.9	0.650

TABLE- 40

Run No.GSP/I/d_{p_2}/h_{s_1}/R_4 Average fluid temp.= 33°C.

1	2		3	4		5	6	7
1	2.9	CCl_4	1151.5	3.3	CCl_4	32.8	-	-
2	5.7	"	1987.2	5.6	"	55.8	-	-
3	8.6	"	2632.0	7.5	"	73.2	-	-
4	12.1	"	3290.0	9.8	"	94.8	-	-
5	21.6	"	4553.4	13.2	"	113.0	-	-
6	32.7	"	5777.2	16.2	"	116.0	-	-
7	42.0	"	6672.1	18.6	"	123.5	-	-
8	60.7	"	8192.1	29.5	"	226.0	-	-
9	70.4	"	8883.0	37.6	"	323.0	1.0	0.166
10	12.1	Hg.	11186.0	8.9	Hg.	775.4	2.0	0.333
11	15.7	"	13028.4	14.0	"	1304.0	2.7	0.450
12	19.5	"	14673.4	18.0	"	1683.0	3.0	0.500
13	24.7	"	16614.5	22.1	"	2006.0	3.6	0.600

VARIATION OF EXPANDED BED HEIGHT AND BED POROSITY WITH FLUID MASS VELOCITY

TABLE-41

Run No.GSE/D/d_{p_1}/h_s /R

w_s = 148.4559 gms.

h_s = 6.8 Cms.

Average fluid temp.= 33°C.

ϵ_{pa} = 0.470

Sl. No.	H_1 Cms.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	2	3	4	5	6
1.	29.7 CCl_4	5461.4	7.0	1.030	0.486
2.	35.0 "	6007.5	7.2	1.059	0.500
3.	40.2 "	6501.0	7.3	1.072	0.505
4.	46.0 "	7007.7	7.5	1.102	0.520
5.	53.0 "	7580.2	8.1	1.191	0.555
6.	56.6 "	7863.1	8.5	1.250	0.576
7.	6.9 Hg.	8093.4	8.7	1.280	0.586
8.	7.7 "	8685.6	9.5	1.398	0.621
9.	9.5 "	9672.6	11.5	1.690	0.686
10.	11.3 "	10791.2	13.0	1.910	0.722
11.	13.5 "	11909.8	14.5	2.133	0.752
12.	14.9 "	12567.8	15.5	2.280	0.768
13.	17.7 "	13883.8	17.5	2.575	0.794
14.	19.3 "	14607.6	19.0	2.795	0.810
15.	21.9 "	15594.6	21.0	3.086	0.828
16.	23.7 "	16252.6	22.5	3.310	0.840
17.	26.9 "	17437.0	24.5	3.604	0.853

TABLE-42

Run No.GSE/D/d_{p_2}/h_s /R

w_s = 149.1727 Gms. Average fluid temp.= 33 °C.

h_s = 6.8 Cms. ϵ_{pa} = 0.351

Sl. No.	H_1 Cms.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	2	3	4	5	6
1.	8.1 CCl_4	2566.2	6.9	1.014	0.360
2.	9.5 "	2796.5	7.0	1.029	0.370
3.	11.5 "	3145.2	7.2	1.058	0.388
4.	13.4 "	3513.7	7.5	1.103	0.411
5.	14.8 "	3671.6	7.9	1.161	0.441
6.	15.2 "	3750.6	8.0	1.176	0.449
7.	17.6 "	4027.0	8.8	1.294	0.499
8.	20.6 "	4434.9	9.5	1.397	0.535
9.	26.8 "	5139.0	10.5	1.544	0.580
10.	28.7 "	5356.1	11.2	1.647	0.606
11.	3.9 Hg.	5658.8	12.0	1.764	0.632
12.	4.9 "	6580.0	13.5	1.985	0.674
13.	5.7 "	7172.2	14.5	2.132	0.696
14.	6.3 "	7632.8	15.5	2.279	0.716
15.	7.9 "	8718.5	17.0	2.500	0.740
16.	9.5 "	9672.6	18.7	2.750	0.764
17.	10.9 "	10528.0	19.5	2.867	0.774
18.	12.5 "	11383.4	21.5	3.161	0.795
19.	13.9 "	12107.2	23.5	3.455	0.813

TABLE-43

Run No.GSE/D/d_{p_3}/h_s /R

w_s = 140.750 gms. Average fluid temp.=32°C.

h_s = 6.8 Cms. ϵ_{pa} = 0.310

Sl. No.	H_1 Cms.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	2	3	4	5	6
1.	1.7 CCl_4	592.2	6.9	1.014	0.320
2.	2.1 "	789.6	7.0	1.029	0.330
3.	2.4 "	921.2	7.1	1.044	0.340
4.	2.9 "	1118.6	7.3	1.073	0.356
5.	3.4 "	1322.6	7.5	1.103	0.375
6.	4.1 "	1566.0	7.8	1.147	0.399
7.	4.4 "	1645.0	8.0	1.176	0.414
8.	5.3 "	1888.5	8.5	1.250	0.449
9.	6.2 "	2118.8	9.0	1.323	0.479
10.	8.0 "	2546.5	9.7	1.426	0.516
11.	9.5 "	2796.5	10.5	1.544	0.553
12.	11.7 "	3211.0	11.5	1.691	0.592
13.	14.5 "	3632.2	12.7	1.867	0.631
14.	17.0 "	3934.8	13.5	1.985	0.652
15.	19.9 "	4336.2	14.5	2.132	0.677
16.	26.0 "	5066.6	16.0	2.352	0.707
17.	31.7 "	5672.0	17.5	2.573	0.732
18.	40.1 "	6481.3	19.5	2.867	0.759
19.	50.1 "	7356.4	21.5	3.161	0.782
20.	58.5 "	8007.9	23.5	3.455	0.801

TABLE-44

Run No.GSE/D/d_{p_4}/h_s /R

w_s = 134.864 gms. Average fluid temp.=32°C.

h_s = 6.3 Cms. ϵ_{pa} = 0.256.

Sl. No.	H_1 Cms.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	2	3	4	5	6
1.	0.6 CCl_4	184.2	6.5	1.034	0.280
2.	0.9 "	296.1	6.9	1.097	0.321
3.	1.3 "	460.6	7.1	1.129	0.340
4.	1.8 "	658.0	7.5	1.193	0.375
5.	2.6 "	1079.1	8.1	1.288	0.421
6.	3.3 "	1269.9	8.7	1.383	0.461
7.	4.0 "	1513.4	9.3	1.479	0.496
8.	5.1 "	1875.3	10.0	1.590	0.531
9.	6.4 "	2191.1	11.0	1.749	0.574
10.	8.5 "	2632.0	12.0	1.908	0.609
11.	9.9 "	2895.2	12.8	2.035	0.634
12.	10.7 "	3040.0	13.5	2.147	0.652
13.	13.3 "	3507.1	14.5	2.306	0.678
14.	15.9 "	3776.9	15.1	2.395	0.689
15.	20.0 "	4336.2	16.5	2.624	0.716
16.	24.1 "	4849.5	17.5	2.783	0.732
17.	29.0 "	5389.0	19.0	3.021	0.753
18.	34.7 "	5987.8	20.5	3.260	0.772
19.	40.3 "	6514.2	22.0	3.498	0.788
20.	45.9 "	6994.5	23.5	3.737	0.801

TABLE-45

Run No.GSE/Cr./d_{p_2}/h_s /R

w_s = 194.799 Gms.   Average fluid temp.=32.5°C

h_s = 7.3 Cms. ϵ_{pa} = 0.500

Sl. No.	H_1		G Kg./Hr.M^2	h_f	$\frac{h_f}{h_s}$	ϵ_f
1	2		3	4	5	6
1.	10.7	CCl_4	3040.0	7.4	1.014	0.507
2.	13.9	"	3566.4	7.5	1.028	0.514
3.	15.7	"	3750.6	7.6	1.041	0.520
4.	18.0	"	4079.6	7.9	1.082	0.538
5.	19.9	"	4336.2	8.1	1.110	0.550
6.	22.1	"	4606.0	8.5	1.165	0.570
7.	28.1	"	5290.3	10.0	1.370	0.635
8.	30.4	"	5527.2	10.5	1.439	0.652
9.	34.0	"	5895.7	11.0	1.507	0.668
10.	4.5	Hg.	6218.1	12.0	1.644	0.696
11.	5.1	"	6744.5	12.8	1.754	0.715
12.	5.9	"	7303.8	14.0	1.918	0.740
13.	6.7	"	7896.0	15.2	2.082	0.760
14.	8.3	"	9014.6	16.9	2.315	0.784
15.	9.9	"	9935.8	18.0	2.466	0.797
16.	11.7	"	10988.6	20.0	2.740	0.817
17.	12.9	"	11580.8	21.5	2.946	0.830
18.	13.9	"	12107.2	22.5	3.083	0.838
19.	15.5	"	12831.0	24.0	3.288	0.848
20.	16.7	"	13423.2	25.0	3.425	0.854
21.	18.1	"	14015.4	26.5	3.631	0.862

TABLE-46

Run No.GSE/Ba/d_{p_2}/h_s /R

w_s = 237.705 gms. Average fluid temp.=32.5°C.

h_s = 6.2 Cms. ϵ_{pa} = 0.415.

Sl. No.	H_1 Cms.		G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	2		3	4	5	6
1.	7.4	CCl_4	2421.4	6.3	1.014	0.425
2.	9.0	"	2730.7	6.4	1.030	0.434
3.	10.4	"	2961.0	6.5	1.047	0.441
4.	12.0	"	3276.8	6.6	1.063	0.450
5.	14.0	"	3586.1	6.9	1.111	0.475
6.	16.0	"	3803.2	7.1	1.143	0.490
7.	17.8	"	4046.7	7.4	1.191	0.510
8.	19.7	"	4303.3	7.7	1.240	0.529
9.	22.9	"	4717.9	8.0	1.288	0.546
10.	26.7	"	5132.4	8.5	1.369	0.574
11.	30.9	"	5593.0	9.0	1.449	0.597
12.	4.2	Hg.	5922.0	9.5	1.530	0.618
13.	5.0	"	6580.0	10.5	1.691	0.655
14.	5.9	"	7303.8	11.5	1.852	0.685
15.	7.3	"	8356.6	12.5	2.013	0.710
16.	9.5	"	9672.6	14.0	2.254	0.741
17.	11.3	"	10725.4	15.5	2.496	0.766
18.	12.3	"	11251.8	16.5	2.657	0.780
19.	13.7	"	12008.5	17.5	2.818	0.783
20.	15.5	"	12831.0	19.0	3.059	0.809
21.	17.7	"	13883.8	20.5	3.301	0.823
22.	19.3	"	14607.6	22.0	3.542	0.835

TABLE-47

Run No.GSE/I/d_{p_2}/h_s /R

w_s = 232.458 gms. Average fluid temp.=33°C.

h_s = 5.9 Cms. ϵ_{pa} = 0.436.

Sl. No.	H_1 Cms.	G Kg./Hr.M^2	h_f Cms.	$\frac{h_f}{h_s}$	ϵ_f
1	2	3	4	5	6
1.	23.8 CCl_4	4803.4	6.0	1.014	0.445
2.	25.7 "	5027.1	6.1	1.031	0.455
3.	26.8 "	5145.6	6.2	1.048	0.463
4.	29.8 "	5461.4	6.5	1.099	0.489
5.	34.5 "	5922.0	7.0	1.183	0.525
6.	38.2 "	6316.8	7.5	1.268	0.556
7.	42.8 "	6711.6	8.2	1.386	0.594
8.	47.0 "	7080.1	8.7	1.470	0.617
9.	6.0 Hg.	7435.4	9.2	1.560	0.638
10.	7.5 "	8488.2	10.5	1.775	0.683
11.	8.7 "	9212.0	11.0	1.859	0.698
12.	9.9 "	9902.9	12.2	2.070	0.728
13.	11.8 "	10988.6	13.5	2.282	0.754
14.	13.6 "	11909.8	15.0	2.535	0.778
15.	14.8 "	12502.0	16.0	2.704	0.792
16.	16.6 "	13357.4	17.5	2.958	0.810
17.	18.8 "	14311.5	19.0	3.211	0.824
18.	21.4 "	15397.2	21.5	3.634	0.845

APPENDIX - C

REPRINTS OF PUBLICATIONS

1. "Fluidized bed heat transfer" (Chem.Proc.& Engg.,Feb.1970)

2. "Prediction of minimum and maximum semi-fluidization velocities by nomographs" (Chem.Age of India, Vol.22,No.9, September 1971)

3. "Relationship between the onset of semi-fluidization velocity and the minimum fluidization velocity", (Indian Jl.of Technol., Vol.10, November 1972)

4. "Prediction of the pressure drop across a gas-solid semi-fluidized bed" (The Chem.Eng.Jl.,5(1973).

5. "Relation Between Maximum Semi-Fluidization and minimum fluidization velocity in liquid-solid systems", (Jl. of the Instn.of Engrs.,India, Vol.54,Feb.1974)

Fluidized bed heat transfer

G. K. ROY & K. J. R. SARMA
Department of Chemical Engineering, Regional Engineering College, Rourkela-8.

ABSTRACT

OUT of the three distinct mechanisms of heat transfer in fluidized beds namely (i) fluid-to-particle, (ii) particle-to-fluid and (iii) wall-to-bed, only the first one has been widely studied and detailed review of the several investigations has been reported earlier by J. J. Barker.[1,2] In the other two cases no such survey has been made and an attempt is made here to give a concise report of the investigations available in literature. The report covers references, majority of which deal with the aspects of study of latter two types of mechanisms of fluidized bed heat transfer. Some important industrial applications of fluidized bed heat transfer have also been discussed.

Introduction

THE varied applications of fluidization technique in chemical and allied industries are recognised and scientific investigations into this field have formed an important and ever-widening proportion of research during the past few years. The pursuit is still on and complete facts about it are yet to be known. The investigations that are already made or yet to be made in this field, can be in the following lines:

(a) Momentum transfer studies
(b) Heat transfer studies
(c) Mass transfer studies

The present article only discusses some salient aspects of heat transfer studies in a fluidized bed.

Heat transfer studies in fluidized bed is a very extensive topic which has drawn the attention of research scientists only during the last two decades. Generally there are three important aspects that are investigated in connection with fluidized bed heat transfer:

(i) Fluid-to-particle heat transfer
(ii) Particle-to-fluid heat transfer
(iii) Wall-to-fluid heat transfer

The discussion here is presented in four sections.

In the first part, the mechanism of heat transfer from fluid to solid particles is discussed. Besides, a brief review of work of a few investigators for predicting fluid-to-particle heat transfer coefficients is also given. The second section includes the physical mechanisms of heat transfer from solid particles to the fluid medium in a fluidized bed and the empirical correlations obtained for different systems by various investigators. The mode of heat transfer from the wall to the fluid and the generalised equations have been dealt with in the third section. In the fourth part, some important industrial applications of the fluidized bed heat transfer mechanism have been discussed.

FLUID-TO-PARTICLE HEAT TRANSFER

Knowledge of the rates of heat transfer from gas to particle is desirable in order to estimate particle surface temperature from the measured temperature of the gas. Such information is especially useful when considering reactions involving large heat effects that occur on and within fluidized catalyst particles. The particle surface temperature affects the reaction kinetics and small changes in temperature often cause large variations in reaction rate. It is also desirable to know actual particle temperature when dealing with heat sensitive materials.

Single-particle theory

It is well known that high rates of heat transfer between solid and gas occur in fluidized beds. This is due to the large surface available for gas-solid contact rather than high heat transfer coefficients. Coefficients are normally in the range of 1-40 Btu/hr. ft^2.°F; whereas heat transfer areas vary from 1,000 to 15,000 ft^2/ft.^{3} of the bed.

The major resistance to heat flow between gas and solid in fluidized bed is to conduction through a thin gas film around the particle. Thus the point coefficients, h_i, is,

$$h_i = k_i / x_i \tag{1}$$

where $x_i = \phi\,(D_p\, V\, \rho/\mu,\ \psi,\ \delta,\ \epsilon)$

Considering this single particle conduction in the line of Fourier, the final heat transfer equation has been derived as,

$$h\, D_p/k = D_p/x + 2 \tag{2}$$

which for an infinite fluid, reduces to the limiting value of 2.

Unsteady state conduction

Due to particle movement in fluidized bed, it would be expected that for a given particle the process is an unsteady one. From dimensional analysis it has been found to be

$$h\ Dp/k = \phi_1\ (D_p\ V\ \rho/\mu)^c\ (C_p\ \mu/k)^f \times \phi_2\ (\epsilon, \psi, \delta) \quad (3)$$

SUMMARY OF WORK

(a) Gas-solid system

Kettenring, Manderfield and Smith[11] were the first to report gas-solid transfer coefficients in case of silica gel and alumina particles of narrow size range, heated and fluidized by air. Walton et. al[23] measured heat transfer coefficients between gas and solids in beds of crushed coal fluidized with air. Wamsley and Johanson[24] investigated gas-to-particle heat transfer in fluidized beds of glass beads, washed alumina and Dowex-50 particles under unsteady state heating condition. The next unsteady state heat transfer studies were due to Fritz[5] followed by Ferron[4]. Heertjes and Mckibbins[7,8] investigated temperature and humidity variations in a drying fluidized bed of wet silica gel fluidized by air. The evaporation of brine solution in fluidized salt bed with high temperature inlet gas was studied by Frantz.[6] The coefficients were correlated with Re. No. although only one particle size of sand was used. Richardson and Ayers[16] also studied heat transfer under steady state but in rectangular vessel. Many type of particles of different sizes were fluidized with air and CO_2. The coefficients were correlated with particle Reynolds no.

Sunkoori and Kaparthi[19] were the only investigators to report heat transfer coefficients between fluidized particles and a liquid medium, and coefficients have been calculated by a modification of the unsteady state method of Wamsley and Johanson.[24] Quartz and granite particles were fluidized with water and equation of Wamsley was used for evaluating heat transfer coefficients.

The results of the above investigators have been summarized by Frantz,[6] and presented in the form of the following table:

All the investigators except Fritz[5] and Ferron[4] have correlated their experimental data using equation containing only the Reynolds number and Nusselt number. These two found appreciable variation of h with the height of the bed and hence correlated their data in terms of velocity of fluid and the length of the bed.

Frantz[6] observed that for the same Reynolds number the values of Nusselt number prediction according to the various equations proposed varied from 0.001 to 2. From dimensional analysis they have observed that the best form of correlation should be of the type

$$Nu = \phi_1\ (Re)^a\ (pr)^b \times \phi_2\ (\psi)$$

From the data of all the above investigators the following two equations — one for gas-solid and the other for liquid-solid fluidization — have been suggested:

Gas-solid system:

$$h\ D_p/k = 0.015\ (Dp\ G/\mu)^{1.6}\ (C_p\ \mu/k)^{0.67} \quad (4)$$

Liquid-solid system:

$$h\ D_p/\kappa = 0.016\ (D_p\ G\ /\ \mu)^{1.3}\ (C_p\ \mu\ /\ \kappa)^{0.67} \quad (5)$$

PARTICLE-TO-FLUID HEAT TRANSFER

The problem of particle-to-fluid heat transfer is widely encountered. Until comparatively recently, all operations involving particle-fluid heat transfer employed fixed and moving beds. A pertinent example is the pebble heater, the contacting unit of which may be fixed or moving bed type. Another and older example is the blast furnace. The charge descends down the furnace shaft and is contacted by a rising stream of hot gases, which is a complicated type of moving bed.

In recent years, applications of particle-fluid heat transfer in the fluidized state have become more

Investigators	Technique used	Correlations used	h range
(1) Kettenring et al.	Steady state gas fluidized	$hD_p/k = .0135\ (D_p\ G/\mu)^{1.35}$	3-10
(2) Walton et. al.	Steady state gas fluidized	$h\ D_p/k = .0028\ (D_p\ G/\mu)^{1.7}\ (D_t/D_p)^{.2}$	5-35
(3) Wamsley et. al.	Unsteady state gas fluidized	$h = 1270\ D_p^{1.27}$	0.07-9
(4) Fritz	Unsteady state gas fluidized	$h = V/(116+52.4\ L_B) + (1-0.62)/\ (274+447L+146L^2)$	0.0005-0.012
(5) Ferron	Unsteady state gas fluidized	"	0.0002-0.06
(6) Heertjes et. al.	Steady state gas fluidized	$h = 1.31\ (D_p\ G/\mu)^{0.76}$	6-28
(7) Frantz	Steady state gas fluidized	$h\ D_p/k = 0.018\ (D_p\ G/\mu)^{1.2}$	0.8-2-0
(8) Sunkoori et. al.	Unsteady state liquid fluidized	$h\ D_p/k = 0.00391\ (D_p\ G/\mu)^{2.1}$	110-620

numerous. But most of the studies of fluidized heat transfer, so far reported are only concerned with heat transfer from an exposed surface to a fluidized medium and suitable empirical correlations are available for predicting the heat transfer rates under conditions similar to those reported in the various investigations. Only a few studies consider the heat transfer from the fluidized particles to the fluidizing medium. But this study becomes essential, especially for the rational design of catalytic reactors.

The problem of the proper temperature difference is the source of much of the difficulty with particle-to-fluid heat transfer in fluidized beds. In systems other than fluidized beds, the problem is usually comparatively simple; the concept of a laminar zone near the surface of a particle and a single relatively homogeneous turbulent zone, next to that (or a well defined laminar region in its place) serves to handle the majority of cases found in practice. In a fluidized bed, however, it appears that the situation is rarely simple. There is good evidence that, especially in gas fluidized beds, the fluid in excess of that required to just fluidize the bed passes through the bed as a particle-pour dispersed phase in a matrix of a "dense" phase which is continuous and which contains the bulk of the particles. The amount of exchange of particles and fluid between the two phases is, for the most part not known, difficult to measure, impossible to guess and appreciably affected by numerous common perturbations in fluidized bed parameters. There are, however the data which must be available before a genuine point coefficient can be determined.

Physical mechanism

The heat transfer from fluidized particles to the surrounding medium depends primarily on the flow around the individual particles. As for spherical particles, as a first approximation of heat transfer coefficients might be made by the equation already derived for the previous case. For this, Reynolds number is based on the particle diameter and free stream velocity past the sphere. By assuminsg uniform distribution of particles, the velocity past the particle (V_p) may be calculated by

$$V_p = V_o \left\{ 1/\left[1-(1-\epsilon)^{0.66} \cdot \pi^{0.33} (0.75)^{0.66} \right] \right\}$$
$$= F\epsilon \, V_o \qquad (6)$$

where, $F\epsilon$ is the velocity correlation factor. The velocity correlation factor $F\epsilon$ can be calculated from the experimental values of bed voidage at various superficial fluid velocities.

Particle interactions play a large role in determining the heat transfer. The frequency with which the particles strike each other, as well as their velocity, influences the degree to which the boundary layers on the particles are distributed. The interaction velocity is dependent on particle density in the fluidized (medium) column. This particle density in turn is dependent on density of the solid material and the particle diameter. These three parameters i.e. μ, ρ_p and D_p can be expressed in the dimensionless forms

$$\mu/\mu_o \; , \; \rho_p/\rho_f \; , \; D_p/D_T$$

which are useful in correlating experimental data, where μ_o is some suitable reference value for viscosity.

Investigations

Heat transfer from single spheres has been reported by Kramers[12] Vliet and Lappert[22] have extended the data previously available and reported the following relation for flow of water and oil over spheres in Reynolds number from 1 to 50,000.

$$N_u \, (Pr)^{-0.3} \, (\mu_w/\mu)^{0.25} = 1.2 + 0.53 \, Re^{0.54} \qquad (7)$$

It is suggested that this relation can be extrapolated to Reynolds number as high as 3×10^5. Van Heerden et. al.[20,21] suggested the importance of the particle convective mechanism of heat transfer in gas fluidized beds. This was substantiated experimentally by Ziegler et al[27] who found that 80 to 95% of the heat transfer was by particle convection. They presented a model for particle convective heat transfer in fluidized beds.

Extensive study was made by Holman, Moore and Wong.[9] Stainless steel and lead spheres were fluidized in water and heated by an induction heating field. Reynolds number based on particle diameter and superficial velocity particles to the water was correlated with:

$$N_u = 1.92 \times 10^{-5} \, (Re \, F\epsilon)^{2.0} \, (Pr)^{0.67}$$
$$(D_T/D_p)^{0.5} \, (\rho_f/\rho_p)^2 \, (\mu/\mu_o)^{.83} \qquad (8)$$

The velocity correlation factor, $F\epsilon$, was introduced to account for variations in porosity.

Effectiveness factor for heat transfer

Information dealing with the transfer of heat from solid particles in the fluidized state to a gas or a liquid flowing past then varies widely, and correlation of the generalised type for heat transfer coefficients are not very common. Lack of progress may be due to experimental difficulties encountered in the evaluation of the proper temperature difference and transfer area associated with such fluidized systems. In addition heat transfer in fluidized system is complicated by the existence and generation of bubbles which produce a non-ideal flow pattern within the bed. These non-ideal conditions give rise to the introduction of effectiveness factors to the conventional heat transfer equations as applied to packed bed conditions.

Petrovic and Thodos[15] have introduced effectiveness factors for the above and have given the heat transfer equation as:

$$q = h_{gb}\, f_t\, f_a\, f_h\, a\, v\, (\triangle t)_m \tag{9}$$

where 'h_{gb}' is the heat transfer coefficient at bubble point (bubble point mass velocity has been found to be equal to 30% above the minimum fluidization mass velocity). Subsequently this has been correlated to the heat transfer coefficient in an actual fluidized bed. Also

$$q = h_{gb}\, \chi\, a\, v\, (\triangle_t)_m \tag{10}$$

where, χ is the overall effectiveness factor.

A normalised heat transfer factor is defined as:

$$g = (JH)_f \;/\; (JH)_b \tag{11}$$

The ratio defines 'g' as,

$$g = (h_{gf} \;/\; h_{gb}) \;.\; (G_b \;/\; G_f) \tag{12}$$

$$\text{or, } h_{gf} = g \;.\; h_{gb} \;.\; (G_f \;/\; G_b) \tag{13}$$

For fluidized bed,

$$q = h_{gf}\;\; a\, v\, (\triangle t)_m$$

$$= g \;.\; h_{gb}\;\; G_f/G_b)\; a\, v\, (\triangle t)_m \tag{14}$$

Since,

$$(G_f/G_b) = (Re_f\;\, Re_b)$$

$$q = h_{gb}\, g \;.\; (Re_f/Re_b) \;.\; a\, v\, (\triangle t)_m \tag{15}$$

From equations (10) and (15)

$$\chi = g\, (Re_f/Re_b) \tag{16}$$

The values of g and R (Re_f/Re_b) corresponding to fluidized runs have been calculated and correlated as

$$g = 1.0/R^{1.13} \tag{17}$$

which gives,

$$\chi = g^{0.115}$$

The authors have also correlated heat transfer factor to porosity as:

$$g = 1.7 \;/\; (\epsilon_f/\epsilon_p)^{2.73} \tag{19}$$

$$\text{for, } \epsilon_f/\epsilon_p > 1.22$$

$$\text{For, } \epsilon_f/\epsilon_p < 1.22,$$

'g' can be taken as unity combining equations (18) and (19).

$$\chi = 1.063 \;/\; (\epsilon_f/\epsilon_p)^{0.314} \tag{20}$$

$$\text{for } \epsilon_f/\epsilon_p > 1.22.$$

From a knowledge of the fluidized bed conditions it is possible to evaluate the effective heat transfer coefficient for the bed, (h_{gf}).

WALL-TO-FLUID HEAT TRANSFER

Physical mechanism

The primary resistance to heat transfer occurs in the thin layer of fluid at the wall of the heated column, and substantially all of the radial temperature drop between wall and fluid occurs in this region. In the central portion of the fluidized column the radial temperature distribution is very uniform. The heat transfer coefficient for fluidized system is substantially higher than for flow systems without the presence of fluidized solids, and the higher values may be explained by the fact that the solids scrub the wall and disturb the laminar sublayer to such an extent that its thickness is decreased or at least there is an injection of turbulence into the layer which decreases the thermal resistance and brings about a high heat transfer rate. The specific heat of solids has been found to affect the heat transfer rate from the heated wall to the fluidized systems. Particles with high specific heats may transport energy from the fluid region near the wall more readily and consequently bring about higher values of heat transfer coefficient.

As the heat transfer characteristics of the fluidized systems are observed over a range of porosity a maximum in the heat transfer coefficient is experienced. After the initial fluidization, the heat transfer coefficient increases with an increase in the mass velocity of the fluid (and corresponding increase in porosity). The coefficient reaches a maximum and then decreases with a further increase in mass flow. The mass velocity corresponding to the maximum heat transfer coefficient has been designated as the dividing line between the so-called dense-phase and dilute-phase fluidization.

An interesting effect in fluidized system has been found out by Frantz[6] and others. In a heated vertical column containing the fluidized solids, the axial temperature profile of the fluid indicates that practically all the temperature rise in the fluid occurs in a shallow region near the bottom of the column and the temperature remains essentially constant above this point. This shallow region is called the "active section". Lemlich and Caldas[13] report that this effect is more pronounced for high Reynolds numbers.

A casual inspection of these results could lead to the conclusion that practically all of the heat transfer occurs in the region near the bottom of the column, even though the entire column is heated. This does not account for the secondary flow regions which may be present in such fluidized systems. Since the solid particles are maintained in suspension by the vertical fluid drag forces, the particle motion will vary with radial distance from the wall of the tube. In the central portion of the tube, velocity is largest and hence the fluid exerts a force on the particles sufficiently strong to cause them to flow upward. Near

Petrovic and Thodos[15] have introduced effectiveness factors for the above and have given the heat transfer equation as:

$$q = h_{gb}\ f_t\ f_a\ f_b\ a\ v\ (\Delta t)_m \tag{9}$$

where 'h_{gb}' is the heat transfer coefficient at bubble point (bubble point mass velocity has been found to be equal to 30% above the minimum fluidization mass velocity). Subsequently this has been correlated to the heat transfer coefficient in an actual fluidized bed. Also

$$q = h_{gb}\ \chi\ a\ v\ (\Delta t)_m \tag{10}$$

where, χ is the overall effectiveness factor.

A normalised heat transfer factor is defined as:

$$g = (JH)_f\ /\ (JH)_b \tag{11}$$

The ratio defines 'g' as,

$$g = (h_{gf}\ /\ h_{gb})\ .\ (G_b\ /\ G_f) \tag{12}$$

$$\text{or, } h_{gf} = g\ .\ h_{gb}\ .\ (G_f\ /\ G_b) \tag{13}$$

For fluidized bed,

$$q = h_{gf}\ \ a\ v\ (\Delta t)_m$$

$$= g\ .\ h_{gb}\ \ G_f/G_b)\ a\ v\ (\Delta t)_m \tag{14}$$

Since,

$$(G_f/G_b) = (Re_f\ Re_b)$$

$$q = h_{gb}\ g\ .\ (Re_f/Re_b)\ .\ a\ v\ (\Delta t)_m \tag{15}$$

From equations (10) and (15)

$$\chi = g\ (Re_f/Re_b) \tag{16}$$

The values of g and R (Re_f/Re_b) corresponding to fluidized runs have been calculated and correlated as

$$g = 1.0/R^{1.13} \tag{17}$$

which gives,

$$\chi = g^{0.115}$$

The authors have also correlated heat transfer factor to porosity as:

$$g = 1.7\ /\ (\epsilon_f/\epsilon_p)^{2.73} \tag{19}$$

for, $\epsilon_f/\epsilon_p > 1.22$

For, $\epsilon_f/\epsilon_p < 1.22$,

'g' can be taken as unity combining equations (18) and (19).

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A casual inspection of these results could lead to the conclusion that practically all of the heat transfer occurs in the region near the bottom of the column, even though the entire column is heated. This does not account for the secondary flow regions which may be present in such fluidized systems. Since the solid particles are maintained in suspension by the vertical fluid drag forces, the particle motion will vary with radial distance from the wall of the tube. In the central portion of the tube, velocity is largest and hence the fluid exerts a force on the particles sufficiently strong to cause them to flow upward. Near the tube wall the fluid velocities are smaller as a result of the viscous action at the boundary and are not large enough to maintain the particle suspension; consequently they move downward in the column. Thus there is an upward motion in the centre of the column and downward near the wall.

The particles near the wall receive energy from the wall and transport it downward into the active section, where it is distributed uniformly among the particles which flow upward. Thus the temperature of the fluid measured at the axis of the flow may under certain conditions, show no substantial increase at points above the active section.

Investigations

Wall-to-fluid heat transfer coefficients are generally very high. Two mechanisms have been proposed to account for the increased heat transfer rates. First, it is suggested that the particles stir the fluid in the bed and thereby decrease the thermal resistance of the film at the heat transfer surface, and secondly the particles transfer heat themselves as they move in and out of the thermal boundary layer at the wall.

Heat transfer coefficients between the wall and a liquid fluidized bed have been measured by Lemlich and Caldas[13], Richardson and Mitson[17], Jagannadharaju[10] and Richardson and Smith[18]. These workers found that the heat transfer coefficients increased markedly as the porosity was decreased from unity, and reached a maximum at a porosity of about 0.75. The coefficients then decreased steadily as the porosity was further reduced to fixed bed condition. All of the workers, except Caldas et. al.[13] reported that the heat transfer coefficients increased with increasing particle size. They also observed that the porosity at which maximum value of heat transfer coefficients occur decreases as the particle size is increased.

Richardson and Smith[18] examined the effect of the thermal properties of the solids upon the heat transfer coefficients by using solids of widely varying properties; glass, iron, copper, lead and gravel. Their empirical correlation of h is:

$$h - h_1 = 1095\,(1 + 35.4\,C_p^{2.12})\,(1-\epsilon)^m \quad (V_o/\epsilon)^{1.15}$$

where,

$h - h_1$ = heat transfer improvement relative to equivalent open pipe flow.

$$m = 0.079\,(\rho_f\,U_o\,d_p\,/\,\mu)^{0.36} \qquad (22)$$

'h' is wall-to-fluid heat transfer coefficient Btu/hr. ft.^{2} °F. The above equation places considerable emphasis on the specific heat of solids, thus suggestes that heat transport by particle convection is quite important. The assumption that the resistance to heat transfer from the wall to a gas fluidized bed is confined to a region very close to the wall seems to be justified since the experimental measurements of several investigators show that the radial temperature profile is extremely steep at the wall and virtually flat across the bulk of the bed. Mickley and Fairbanks[14] studied the nature of the resistance controlling heat transfer between the fluidized beds and surfaces in contact with them. They observed that unsteady state diffusion of heat into mobile elements of quiescent bed material to be the controlling factor for heat transfer. Further they noted that the heat transfer coefficients are proportional to the square root of the thermal conductivity of the quiescent bed.

Wasmund and Smith[25] developed a model for predicting the rate of heat transfer by particle convection in liquid fluidized beds which was based on radial temperature profiles and particle velocities. They reasoned that a particle entering the thermal boundary layer at the wall absorbed heat from its surroundings proportional to the temperature driving force which varies continuously as the particle approaches and departs from the wall. They obtained solutions for two cases, (i) the thermal conductivity of the particles is large, hence the film surrounding the particles is the controlling resistance (ii) the thermal conductivity of the particles is small, and as a result its resistance must also be considered. Their solution for the particle convective heat transfer coefficient, h_o, for case (i) is:

$$h_o = \frac{(1-\epsilon)\; v_r\; \rho_p\; C_p\; (e^{-bc} - 1)^2}{2 \qquad\qquad bc}$$

where,

$c = 6\,h_p\,/\,d_p\;\rho_p\;C_p\;v_r$

b = thickness of the thermal boundary layer at wall.

Later calculations, based on the temperature profiles of the present investigation, indicate that particle convective mechanism is considerably less important in liquid fluidized beds.

Later Wasmund and Smith[26] studied wall-to-fluid heat transfer with an aim to investigate the effect of the thermal conductivity of the solids on transfer coefficients.

All the fluidized bed heat transfer experiments were conducted at a constant bed height of 25-in. The porosity was adjusted by adding known weights of the particles through the spout in the expansion section. Porosities were varied from 0.95 to 0.45, the latter being minimum fluidization porosity. The water temperature at the inlet to the test section was maintained at 77±0.5°F for all runs. The temperature driving force, (T_W-T_B), was kept small for all runs in the order of 5 to 10°F, to minimize changes in the physical properties of the water. Heat transfer coefficients were calculated from the equation—

$$h_w = (q_w\,/\,(T_W - T_B) \qquad (22)$$

where, $(T_W - T_B)$ is the temperature difference of the wall and the bulk stream measured $16\frac{1}{2}''$ above the bottom of the heating section.

Typical results of the heat transfer experiments in glass and aluminium systems were reported, where the coefficients are plotted as functions of porosity. Since the porosity is a unique function of the velocity for any given sphere size and solids density the heat transfer coefficients for each system are represented by curves in a single plot.

The heat transfer curves for each particulate system passed h_{max} and the porosity at which the max mum occurs decreases with increasing particle size; an effect which was also observed by Richardson and Smith[18] and Ruckenstein **et. al.** The maximum values of **h**, for the glass and aluminium systems were correlated by the following equation which fitted the data well for $D_p > 0.02''$.

$$h_{max} = 2060 + 640 \log D_p \qquad (23)$$

The observation that h_{max} increases with particle size is in agrement with all of the previous investigations of liquid fluidized heat transfer except that of Lemlich and Caldas.[13]

Heat transfer coefficients at the wall

Wall coefficients for the fluidized glass system are plotted as Stanton numbers (St_u) vs. porosity on semi-logarithmic co-ordinates. It is observed that Stanton number increases linearly with decreasing porosity for $0.45<\epsilon<0.90$. For porosities greater than 0.90, Stanton number decreases sharply. It is also noteworthy that at any given porosity, Stanton number increases with decreasing particle size. The following correlations were obtained for the film Stanton number for the glass and aluminium particles.

$$\text{Glass: } St_w = 10^{(.11-1.75\,\epsilon)}\,Re^{-0.33} \qquad (24)$$

$$\text{Aluminium } St_w = 10^{(0.29-1.75\,\epsilon)}\,Re^{-0.37} \qquad (25)$$

This shows that Stanton number for aluminium is larger than for glass particles. It is clear that solids thermal conductivity also influences the heat transfer mechanism at the wall, particularly at low voidages. This is reasonable because the temperature gradient at the wall is extremely steep, and as a result heat conduction through the particles is enhanced by the large temperature drop across the particles.

Conclusions

(1) Heat transport by particle convection is insignificant in the process of wall-to-fluid heat transfer in liquid fluidized beds, except possibly at low porosities. In this regard fluidization by gases and liquids are distinctively different because particle convection is the predominant mechanism of heat transfer in gas fluidized beds.

(2) Fluid convection is the main mechanism of heat transfer in liquid fluidized beds; particle convection and conduction are of minor importance at low porosities.

(3) The resistance to heat transfer in a liquid fluidized bed shifts progressively from the region near the pipe wall to the bulk of the bed as the porosity is decreased from unity.

(4) Effective thermal diffusivities in the bed, calculated from the radial temperature profile decrease nearly linearly with porosity for $E_r<0.9$.

(5) A series mechanism of heat transfer suggest a correlation of the form:

$$1/St = 1/St_w + UD_T/8E_r \qquad (26)$$

This correlation shows a dependence on column diameter which should be tested experimentally. This correlation also correlates wall-to-fluid heat transfer coefficients obtained in the water fluidized beds of glass and aluminium spheres with an average deviation of less than 10% for particle diameter ranging from 0.112″ to 0.02″ in the porosities ranging from 0.9 to 0.45.

Industrial applications

One of the novel characteristics of fluidized beds is the uniformity of temperature found throughout the system. Essentially constant temperature is known to exist in both horizontal and vertical directions in beds from 1″ to 30′ in diameter. Temperature variations occur in some beds near zones where large quantities of relatively hot or cold particles are injected; however, these temperature variations are generally small. The isothermal conditions found in fluid beds make them ideal for many catalytic reactions, since yield and selectivity of the catalyst depend to a large extent on both temperature level and uniformity. Thus an important application of fluidized bed heat transfer is in the design of commercial catalytic reactors. Especially the particle-fluid heat transfer study finds its use for the rational design of catalytic reactors as it has been recognised that, the prediction of particle-fluid heat or mass transfer coefficients is important in the course of the estimation of local or overall conversions. It is also necessary to know these heat transfer rates in order to design a fluidized nuclear reactor. With this end in view experimental study was initiated by Holman **et. al.**[9] to determine the heat transfer coefficients for lead spheres fluidized in water and it is anticipated that the data will be applicable to natural-uranium water fluidized nuclear reactor.

Another important industrial application of the fluidized bed heat transfer is the fluidized bed drying. Of late, this fluidized bed technique has met with wide and growing acceptance in chemical and allied industries for drying of relatively free flowing granular materials in a wet state. Conventional dryers like, continuous through-circulation type and pneumatic conveying type were earlier performing similar duties and are still preferred for some specific situations. But, fluidized bed dryers are holding the ground firmly now-a-days because they command several selective advantages over conventional types. Compact unitised design, intimate gas-solid contact resulting in uniform material treatment with a wide range of materials, close temperature control minimum operating attention and maintenance costs and high thermal efficiency are among the proved advantages.

Scope

The influence of particle shape and void fraction have not been extensively studied and incorporated in the general expressions for heat transfer coefficient for gas-solid as well as liquid solid systems. More work is needed in liquid fluidized bed to carry out the studies of the influence of Prandtl numbers.

NOMENCLATURE

a	=	Interfacial area of packing, L^{-1}
A	=	Area of fluidized bed participating in heat transfer, L^2
C_p	=	Heat capacity, QMT^{-1}
D_p	=	Diameter of particle, L
D_T	=	Diameter of column, L.
E_r	=	Radial thermal diffusivity, $L^2\ \theta^{-1}$
$F\epsilon$	=	Velocity correlation factor, dimensionless,
f_a	=	Effectiveness factor for area dimensionless
f_h	=	Effectiveness factor for heat transfer coefficient, dimensionless.
f_t	=	Effectiveness factor for temperature coefficient dimensionless.
G	=	Superficial mass velocity, $M\ \theta^{-1}\ L^{-2}$
G_b	=	Superficial mass velocity, at bubble point, $M\ \theta^{-1}\ L^{-2}$.
G_f	=	Superficial mass velocity of fluidized bed, $M\ \theta^{-1}\ L^{-2}$.
g	=	Normalised heat transfer factor, dimensionless.
h_o	=	Particle convection heat transfer coefficient, $Q\ \theta^{-1}\ L^{-2}\ T^{-1}$
h_{gb}	=	Heat transfer coefficient at bubble point, $Q\ \theta^{-1}\ L^{-2}\ T^{-1}$.
h_{gf}	=	Heat transfer coefficient of fluidized bed, $Q\ \theta^{-1}\ L^{-2}\ T^{-1}$.
h_{max}	=	Maximum value of the heat transfer coefficient in fluidized bed, $Q\ \theta^{-1}\ L^{-2}\ T^{-1}$.
h_p	=	Particle-to-fluid heat transfer coefficient in fluidized bed, $Q\ \theta^{-1}\ L^{-2}\ T^{-1}$.
h_w	=	Wall-to-fluid heat transfer coefficient in fluidized bed, $Q\ \theta^{-1}\ L^{-2}\ T^{-1}$.
JH	=	Heat transfer factor $(h/C_p\ G)\ (C_p\ \mu/k)^{0.66}$
$(JH)_b$	=	Heat transfer factor at bubble point.
$(JH)_f$	=	Heat transfer factor of fluidized bed.
K (k_t or k_f)	=	Thermal conductivity of the fluid $Q\ \theta^{-1}\ L^{-1}\ T^{-1}$
L	=	Length of column, L.
L_B	=	Height of bed, L.
N_u	=	Nusselt number, $h\ D_p/k$, dimensionless.
Pr	=	Prandtl number, $C_p\ \mu/k$ dimensionless.
q	=	Rate of heat transfer in the bed, $Q\ \theta^{-1}$.
q_w	=	Rate of heat input to the wall (as calculated from electrical power consumption), $Q\ \theta^{-1}$.
Re	=	Reynolds number, $D_p\ G/\mu$, diamensionless.
$(Re)_b$	=	Reynolds number, at bubble point, dimensionless.
$(Re)_f$	=	Reynolds number for fluidized bed, dimensionless.
R	=	Normalised Reynolds number, $(Re)_f/(Re)_b$
St_w	=	Stanton number with respect to column wall, dimensionless.
T_W	=	Wall temperature, T.
T_B	=	Bulk stream temperature, T.
$(\triangle t)_m$	=	Log mean temperature difference, T.
U	=	Average superficial velocity, $L\theta^{-1}$
U_o	=	Velocity obtained by extrapolating Richardson-Kaki. Curves to unity porosity, $L\theta^{-1}$.
U_p	=	Average particle velocity, $L\theta^{-1}$.
V_p	=	Free stream velocity past the particles, $L\theta^{-1}$.
V_o	=	Superficial velocity in the tube (velocity at 100% porosity) $L\theta^{-1}$.
V_r	=	Average velocity of particles in radial direction, $L\theta^{-1}$.
V	=	Volume of the bed, L^3.
x_l	=	Point film thickness of fluid, L.

GREEK LETTERS

ϵ	=	Void fraction.
ϵ_p	=	Void fraction of packed bed.
ϵ_f	=	Void fraction of fluidized bed.
δ	=	Particle roughness.
ψ	=	Particle shape factor.
ρ_f (ρ)	=	Fluid density, ML^{-3}.
μ (μ_f)	=	Fluid viscosity, $ML^{1-}\ \theta^{-1}$.
χ	=	Overall effectiveness factor for heat transfer, $f_a\ .\ f_t\ .\ f_h$.

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PREDICTION OF MINIMUM AND MAXIMUM SEMIFLUIDIZATION VELOCITIES BY NOMOGRAPHS.

by

G. K. Roy*, P. Sen Gupta & K. J. R. Sarma**

Chemical Engineering Department,

Indian Institute of Technology,

Kharagpur.

Semi-fluidization is a new and novel technique of contacting solids with fluid. This can be viewed as a combination of a batch fluidized bed at the bottom and a fixed bed at the top. Such a bed can be obtained by providing sufficient space for the free expansion of the bed and then arresting the escape of the particles out of the system by means of a top restraint. A bed of this nature has the unique advantage[2] in that it combines the merits of packed as well as fluidized bed, which are very essential for the design of mixed and tubular reactors[1] (MT reactors).

Minimum and Maximum Semi-fluidization velocities:

Minimum semi-fluidization velocity is the fluid velocity at which the first particle of the bed touches the top restraint. The velocity, at which all the particles of the bed accumulate below the top restraint is defined as the maximum semi-fluidization velocity. Fan et al[3,4] studied both liquid-and gas-solid systems involving closed size range of particles. They have suggested a dimensionless correlation for the formation of semi-fluidized bed in terms of minimum fluidization velocity, semi-fluidization and maximum semi-fluidization velocities. Poddar and Dutt[5] have recently reported equations based on theoretical considerations to predict the minimum and maximum semi-fluidization velocities for liquid - solid systems. Based on their experimental data, Roy and Sarma[6] have given correlations for the direct prediction of the maximum semi-fluidization velocity, from which the minimum semi-fluidization velocity can be calculated knowing the properties of the liquid and the solid particles and the position of the restraining screen. The proposed correlations are:

(i) For maximum semi-fluidization velocity (G_{msf}) the suggested equation is:

$$G_{msf} = 0.3\ (Ar)^{0.58}\ \left(\frac{\mu}{d_p}\right) \quad \ldots\ldots\ldots\ldots\ldots (1a)$$

With water as the medium the equation reduces to—

$$G_{msf} = 2.675\times10^{4}\ (d_p)^{0.74}\ [\rho_s(\rho_s - \rho_f)]^{0.58} \quad \ldots(1b)$$

(ii) For minimum semi-fluidization velocity (G_{osf}) the equation is —

$$\frac{G_{osf}}{G_{msf}} = 0.105R + \frac{\log(Ar) + 2.456}{52} \quad \ldots (2a)$$

For water-solid system this becomes

$$\frac{G_{osf}}{G_{msf}} = 0.105R + 0.0577 \log d_p + 0.0192 \log [\rho_s\ (\rho_s - \rho_f)]^{+0.2016} \quad \ldots\ldots\ldots\ldots (2b)$$

Based on the above two equations, the two, following, nomographs have been prepared for direct prediction of the maximum (from figure No. 1) and minimum (from figure No. 2 with the help of figure No. 1) semi-fluidization velocities.

Accuracy of the nomograph.

The values found from the nomographs were compared with the respective values obtained by the other two methods, viz, from the equations and the actual experiments. The percentage deviations were also calculated.

Example:

System:- dolomite - water

Particle size (d_p) - 0.008 ft. Particle density (ρ_s) -172.2 lb/ft^3

Fluid density (ρ_s) - 62.4 lb/ft^3. Fluid viscosity (μ) 0.8 CP.

* Chemical Engineering Department,

** Regional Engineering College, Rourkela.

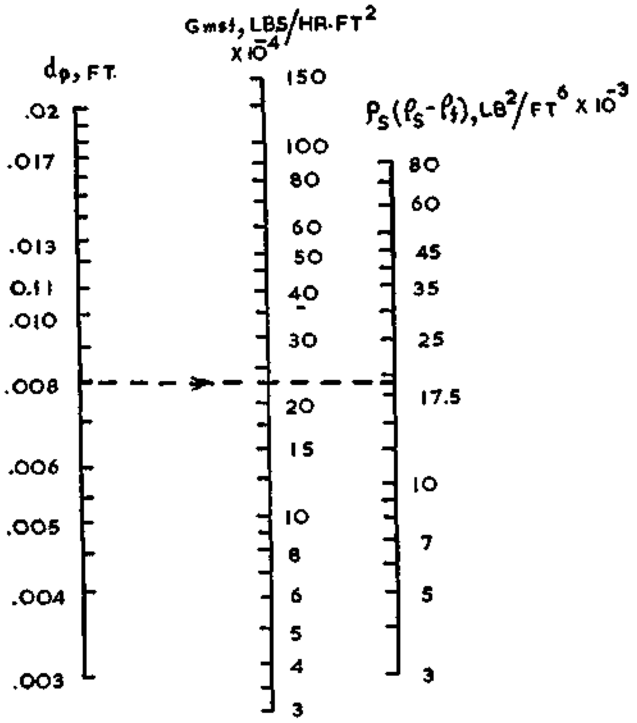

FIG. 1. PREDICTION OF MAXIMUM SEMIFLUIDIZATION VELOCITY.

Bed expansion ratio (R) - 3.0

Maximum semi-fluidization velocity:

(i) From equation —

$$Ar = \frac{d_p^3\ g_c \rho_g (\rho_s - \rho_f)}{\mu^2}$$

$$= \frac{(0.008)^3 \times (32.2) \times (3600)^2 \times 172.2 \times (172.2-62.4)}{(0.8 \times 2.42)^2}$$

$$= 1.08 \times 10^6$$

$$G_{msf} = 0.3\ (Ar)^{0.58} \left(\frac{\mu}{d}\right)$$

$$= 0.3\ (1.08 \times 10^6)^{0.58} \left(\frac{0.8 \times 2.42}{0.008}\right)$$

$$= 2.3 \times 10^5 \text{ lbs/hr. ft}^2$$

(ii) From experiment —

$G_{msf} = 2.26 \times 10^5$ lbs/hr. ft^2

(iii) From nomograph —

$G_{msf} = 2.3 \times 10^5$ lbs/hr. ft^2

Minimum semi-fluidization velocity:

(i) From equation —

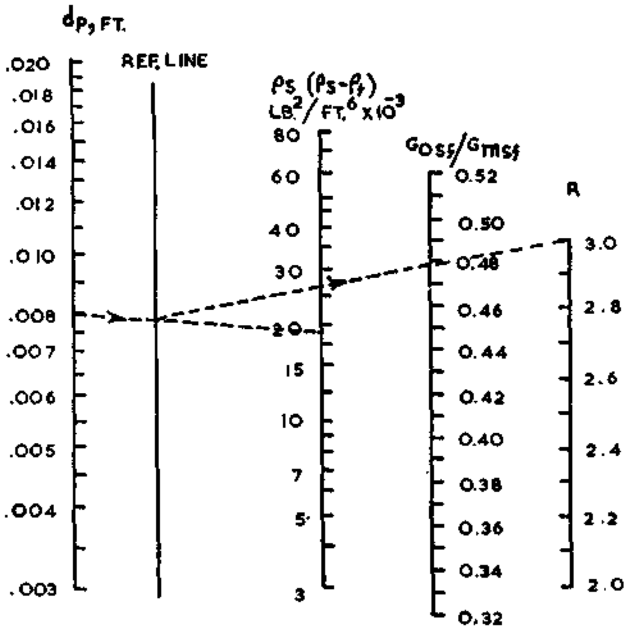

FIG. 2 PREDICTION OF VELOCITY RATIO G_{OSF}/G_{MSF}.

$$\frac{G_{osf}}{G_{msf}} = 0.105R + \frac{\log\ (Ar) + 2.456}{52}$$

$$= 0.105\ (3) + \frac{\log\ (1.08 \times 10^6) \times 2.456}{52}$$

$$= 0.478$$

$$G_{osf} = 0.478 \times G_{msf}$$

$$= 0.478 \times 2.3 \times 10^5 = 1.099 \times 10^5 \text{ lbs/hr ft.}^2$$

(ii) From experiment —

$G_{osf} = 1.08 \times 10^5$ lbs/hr ft^2

(iii) From nomograph —

$$\frac{G_{osf}}{G_{msf}} = 0.4775$$

$G_{msf} = 2.3 \times 10^5$ (from fig. No. 1)

$G_{osf} = 0.4775 \times 2.3 \times 10^5$

$= 1.092 \times 10^5$ lbs/hr. ft.^{3}

Table - 1

Comparison of G_{msf} values.

Values of G_{msf}, lbs/hr.ft.^{2}			Percentage deviation	
Nomograph	Experimental	Calculated	From Expt. Value	From Calculated Value
2.3×10^5	2.26×10^5	2.3×10^5	1.77	0.00

Table - 2

Comparison of G_{osf} values

Values of G_{osf}, lbs/hr.ft.^{2}			Percentage deviation	
Nomograph	Experimental	Calculated	From Expt. value	From Calculated Value
1.092×10^5	1.08×10^5	1.099×10^5	1.11	0 63

Conclusion:

It is seen that the values of minimum and maximum semi-fluidization velocities obtained from nomographs compare favourably with those calculated by the equations and also with the experimental data. The deviations were found to be less than 2 per cent

Nomenclature:

Ar — Archimedes number, $d_p^3 g_c \rho_s (\rho_s - \rho_f)/\mu^2$, dimensionless.

d_p — Particle diameter, ft.

G_{osf} — Onset of semi-fluidization velocity or, minimum semifluidization velocity lbs/hr. ft.^{2}

G_{msf} — Maximum semi-fluidization velocity, lbs/hr. ft.^{2}

R — Bed expansion ratio, i.e. ratio of the top restraint height from the bottom restraint to the initial fixed bed height.

Greek letters:

$_s$ — density of solid, lbs/ft.^{3}

ρ_f — density of fluid lbs/ft^3

μ — viscosity of fluid, lb/ft.hr.

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Relationship between the Onset of Semi-fluidization Velocity & the Minimum Fluidization Velocity

G. K. ROY* & P. SENGUPTA
Department of Chemical Engineering, Indian Institute of Technology, Kharagpur

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Data on the semi-fluidization characteristics of a few gas-solid systems have been obtained. The correlation, $G_{osf}/G_{mf} = A\left(\frac{D_c}{d_p}\right)^{a_1}\left(\frac{\rho_s}{\rho_f}\right)^{a_2}(R)^{a_3}$, relating the onset of semi-fluidization velocity (G_{osf}) with the minimum fluidization velocity (G_{mf}) has been developed in terms of various system parameters (D_c, column diameter; d_p, particle diameter; ρ_s, ρ_f, densities of solid and fluid respectively; and R, bed expansion ratio in state of semi-fluidization). The values of the constants A, a_1, a_2 and a_3 are $2{\cdot}66\times10^{3}$, 0·62, −1·0, 0·5 and $3{\cdot}4\times10^{3}$, 1·11, −1·78, 0·89 for non-spherical and spherical particles respectively.

SEMI-FLUIDIZATION, a recent development in the field of fluid-solid contact operations, is highly suitable for mixed and tubular reactors[1]. A semi-fluidized bed is a compromise between the packed and the fluidized bed conditions, eliminating certain drawbacks of both these operations[2]. The introduction of a porous disc or sieve in a conventional fluidizer arrests the free upward motion of the particles and results in the formation of a semi-fluidized bed consisting of a top packed section and a bottom fluidized portion.

Investigations dealing with the various aspects of liquid-solid semi-fluidization[3] have been reviewed by Roy and Sarma[4,5]. Very little information is available in the field of gas-solid semi-fluidization. In a recent communication[6], the present authors reported some data on gas-solid semi-fluidization. This paper presents a correlation, which relates the ratio of the minimum semi-fluidization velocity to the minimum fluidization velocity with the system parameters.

Experimental Procedure

The set-up used (Fig. 1) is a conventional semi-fluidizer made of perspex column of 4·5 cm int. diam. and 57 cm length. The bottom grid consists of a 150 mesh screen. The movable restraint is made of 80 mesh brass screen. The air flow rate was measured by an orificemeter. The bed pressure drops were measured with the help of two sets of manometers. While taking a run, a definite amount of material is charged into the column and the bed height noted. The movable restraint is adjusted for a fixed bed expansion ratio. With increase in air flow rate, pressure drops across the bed and the top bed formations are noted. The static and expanded bed porosities are determined in separate experiments. The surface area of the particles and the shape factor have been determined by the air permeability method[7].

Results and Discussion

Two spherical and four non-spherical materials of different size fractions were used (Table 1). In Fig. 2, a typical plot of bed pressure drop against fluid mass velocity is given. The onset velocities of semi-fluidization have been evaluated from similar plots and are given in Table 2.

Prediction of minimum semi-fluidization velocity from minimum fluidization velocity — The onset of fluidization and semi-fluidization represent the two consecutive sequences of operations of the semi-fluidization phenomena. While the former corresponds to the initiation of particle movement in a fluid-solid bed, the latter indicates the fluid velocity at which the first particle of the bed touches the top restraint of the semi-fluidizer. For finding the minimum fluidization velocity, several correlations are available in literature[8]. One of the most generalized equations is the one derived by Leva and coworkers[9], which is valid over a wide range of

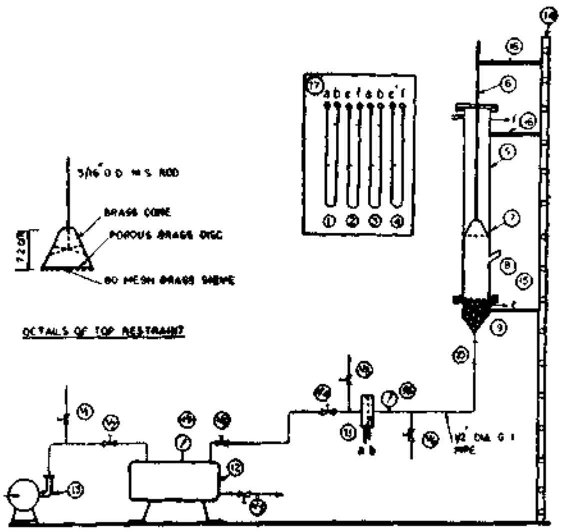

Fig 1 — Experimental set-up: Schematic diagram [(1), (3) manometers for orificemeter; (2), (4) manometers for bed; (5) semi-fluidizer, (6) movable restraint assembly; (7) top restraint, (8) inclined feeder; (9) distributor, (10) flexible connection; (11) orificemeter, (12) reservoir; (13) compressor; (14) structure, (15) base plate support, (16) clamp, (17) manometer panel board; (18) line pressure gauge; (19) reservoir pressure gauge; V_1, V_5, V_7 bypass valves; V_2, V_3, V_4 control valves; and V_6 solid valve]

*Present address: Department of Chemical Engineering, Regional Engineering College, Rourkela 8.

TABLE 1 — PHYSICAL CHARACTERISTICS OF MATERIALS USED

Material	Particle size		Density (ρ_s) g/cc	Packed bed porosity (ϵ_{pa})	Surface area (S_v) cm^2/m^3	Sphericity (ϕ_s)
	Mesh No. BSS	Size (d_p) $m \times 10^4$				
NON-SPHERICAL						
Table salt	20/30	7·51	2·100	0·596	241·0	0·331
do	30/40	4·42	2·100	0·588	300·5	0·452
do	40/52	3·38	2·100	0·560	302·0	0·587
do	52/60	2·74	2·100	0·533	335·0	0·654
Ammonium sulphate	30/40	4·42	1·763	0·377	136·0	1·000
Sand	30/40	4·42	2·650	0·451	170·5	0·798
Magnesite	30/40	4·42	2·800	0·443	177·0	0·770
SPHERICAL						
Mustard seed	14/20	11·05	1·120	0·362	54·2	1·000
Sago	14/20	11·05	1·304	0·380	54·2	1·000

TABLE 2 — CALCULATED AND EXPERIMENTAL MINIMUM SEMI-FLUIDIZATION VELOCITY DATA

System	d_p $m \times 10^4$	G_{mf} kg/hr m^2	R	G_{osf} kg/hr m^2 (exp.)	$\frac{G_{osf}}{G_{mf}}$	G_{osf} kg/hr m^2 [from Eq. (4)]	Deviation of calc. from exp. value %
NON-SPHERICAL							
Table salt-air	7·51	804	2·0	2200	2·74	2215	+0·70
			2·5	2650	3·30	2480	−6·40
			3·0	2900	3·61	2715	−6·38
			3·5	3250	4·05	2925	−10·00
do	4·42	491	2·0	1350	3·76	1887	+2·00
			2·5	2000	4·07	2115	+5·75
			3·0	2275	4·64	2310	+1·27
			3·5	2600	5·30	2500	−3·84
do	3·38	390	2·0	1462	3·75	1770	+21·00
			2·5	1675	4·30	1970	+17·60
			3·0	2025	5·20	2165	+6·90
			3·5	2225	5·71	2340	+5·16
do	2·74	258	2·0	1250	4·85	1330	+6·40
			2·5	1550	6·00	1490	−3·87
			3·0	1850	7·16	1630	−11·90
			3·5	1950	7·55	1760	−9·75
Ammonium sulphate-air	4·42	349	2·0	1750	5·01	1592	−9·04
			2·5	2050	5·87	1785	−12·90
			3·0	2550	7·30	1955	−23·40
			3·5	2850	8·16	2106	−26·10
Sand-air	4·42	653	2·0	1850	2·38	1985	+7·30
			2·5	2050	3·14	2220	+8·30
			3·0	2450	3·75	2428	−0·90
			3·5	2750	4·21	2625	−4·55
Magnesite-air	4·42	596	2·0	1875	3·14	1720	−8·38
			2·5	2100	3·52	1924	−8·38
			3·0	2500	4·20	2106	−15·75
			3·5	2900	4·86	2275	−21·50
SPHERICAL							
Mustard seed-air	11·05	1200	2·0	2450	2·04	2375	−3·06
			2·5	2800	2·33	2900	+3·57
			3·0	3400	2·83	3405	+0·15
			3·5	4000	3·33	3910	−2·25
Sago-air	11·05	1665	2·0	2500	1·50	2530	+1·20
			2·5	2900	1·74	3080	+6·20
			3·0	3500	2·10	3600	+2·86
			3·5	4100	2·46	4160	+1·46

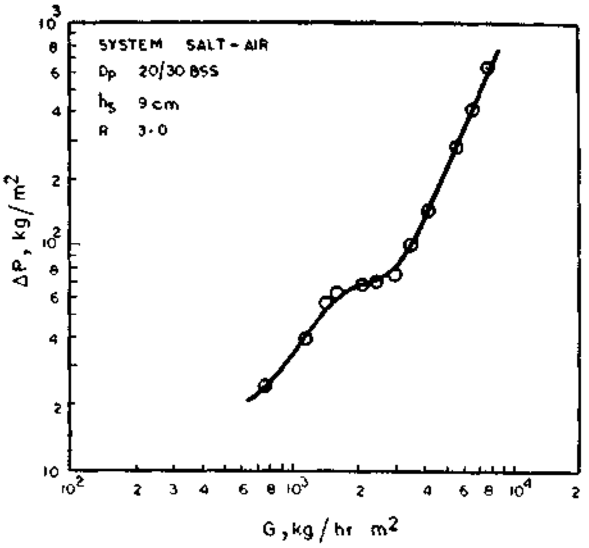

Fig 2 — Variation of pressure drop with fluid mass velocity

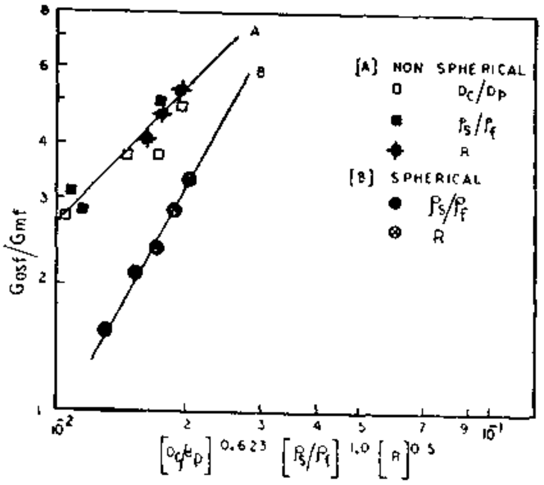

Fig 3 — Correlation plot of G_{osf}/G_{mf} with system variables

variables. Thus, G_{mf} is given as

$$G_{mf} = \frac{0{\cdot}005\, g_c \rho_f(\rho_s - \rho_f) d_p^2 \phi_s^2}{\mu} \frac{\epsilon_{pa}^3}{(1-\epsilon_{pa})^2} \quad \ldots(1)$$

The calculated values of G_{mf} and the ratios of G_{osf}/G_{mf} for the systems studied are given in Table 2.

It is intuitive that both in fluidization and semi-fluidization, the properties of the fluid and the solid as well as the geometry of the system will influence the onset conditions. Among the variables encountered, the important ones are: h_s, D_c, d_p, ρ_s, ρ_f and R. Writing in the form of dimensionless groups

$$\frac{G_{osf}}{G_{mf}} = \phi\left[\frac{h_s}{D_c}, \frac{D_c}{d_p}, \frac{\rho_s}{\rho_f}, R\right] \quad \ldots(2)$$

It has been observed in the course of investigations that variation in bed height does not appreciably affect the velocity of onset of semi-fluidization. Ignoring the effect of h_s/D_c, the expression reduces to

$$\frac{G_{osf}}{G_{mf}} = A\,\{(D_c/d_p)^{a_1}(\rho_s/\rho_f)^{a_2}(R)^{a_3}\} \quad \ldots(3)$$

The exponents a_1, a_2 and a_3 have been evaluated experimentally. In Fig. 3 the values of the ratio G_{osf}/G_{mf} are plotted on a log-log paper against the product $\{(D_c/d_p)^{0.623}(\rho_s/\rho_f)^{-1.0}(R)^{0.5}\}$. Two different straight lines, one for the spherical and the other for the non-spherical particles, have been obtained. For the non-spherical particles, the slope of the line was 1·0 and for the spherical ones it was 1·78. The final correlations can be given as:

For non-spherical particles:

$$\frac{G_{osf}}{G_{mf}} = 2{\cdot}66\times10^2(D_c/d_p)^{0.62}(\rho_s/\rho_f)^{-1.0}(R)^{0.5} \quad \ldots(4a)$$

For spherical particles:

$$\frac{G_{osf}}{G_{mf}} = 3{\cdot}4\times10^3(D_c/d_p)^{1.11}(\rho_s/\rho_f)^{-1.78}(R)^{0.89} \quad \ldots(4b)$$

The values of G_{osf} calculated from Eqs. (4a) and (4b) have been found to be in good agreement with the experimental data. The deviations are given in Table 2, and it is seen that the spherical materials show lesser deviation.

It should, however, be noted that the present study was confined only to two spherical materials and as such, the effect of sphericity, if any, could not be properly ascertained. Further work to study this aspect is necessary.

Nomenclature

D_c = diam of column, L
d_p = particle diam, L
g_c = gravitational constant, $L\theta^{-2}$
G = mass velocity of fluid, $M\theta^{-1}L^{-2}$, subscript mf for minimum fluidization and osf for onset of semi-fluidization
h = height of column, L; subscript pa for packed bed and s for static bed
ΔP = pressure drop across semi-fluidized bed, FL^{-2}
R = bed expansion ratio in semi-fluidization, dimensionless
S_0 = surface area of particles per unit volume of solid, L^2/L^3
ϕ = function
ϕ_s = sphericity of particles
μ = viscosity, $M\theta^{-1}L^{-1}$
ρ = density, ML^{-3}
ϵ = bed porosity

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Short Communications

Prediction of the pressure drop across a gas–solid semi-fluidized bed

G K ROY* and P SEN GUPTA

Department of Chemical Engineering Indian Institute of Technology Kharagpur W Bengal (India)

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The necessity of having a generalized correlation for the prediction of the pressure drop across a semi-fluidized bed is stressed Pressure drops across the semi-fluidized bed have been calculated using various theoretical equations and have been compared with the experimental values For the first time, two different equations, one for spherical particles and the other for non-spherical ones, have been suggested for the prediction of the actual pressure drop in terms of the system variables

Semi-fluidization is a new and unique type of fluid-solid contact operation, which has only been reported in the last decade Like packed bed and fluidized bed operations, this is also a two-phase phenomenon A semi-fluidized bed is a compromise between the packed bed and fluidized bed conditions, in which certain drawbacks of both these operations are eliminated[1] The introduction of a porous disc or sieve in a conventional fluidizer arrests the free upward motion of the particles, resulting in the formation of a semi fluidized bed– the combination of a packed bed at the top and a fluidized portion at the bottom

In the field of semi-fluidization, more attention has been paid to the momentum transfer aspects than to other studies Although some information is available for the prediction of the minimum and maximum semi-fluidization velocities, and also for the prediction of packed bed formation in semi-fluidization information for finding the pressure drop across the bed is scanty An attempt has therefore been made to develop correlations for the prediction of the pressure drop across a gas–solid semi-fluidized bed

Experimental

The experimental set-up used in the present study is shown in Fig 1 The semi-fluidizer was a Perspex column 4 5 cm in internal diameter and 57 cm long The bottom grid was a 150 mesh stainless steel screen

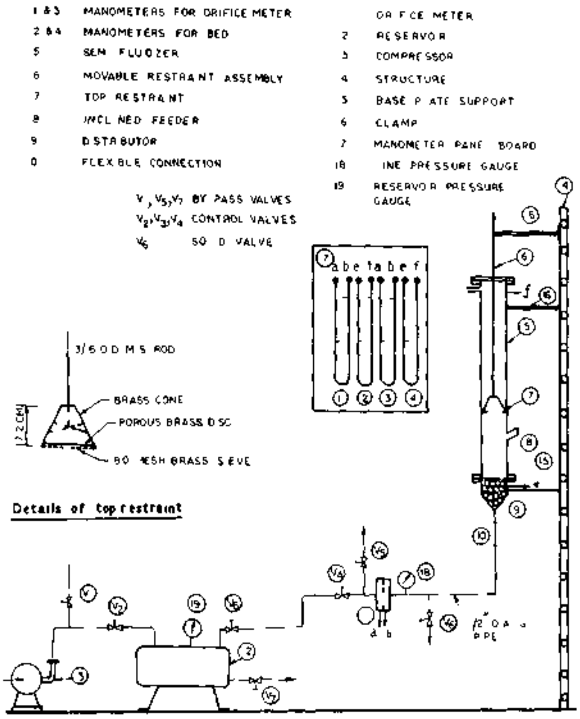

Fig 1 Schematic diagram of the experimental set-up

A movable restraint made from a porous brass plate and an 80 mesh brass screen, both soldered to a brass cone, was fixed rigidly to a mild steel rod $\frac{3}{16}$ in in diameter extending from the top of the semi fluidizer Two pressure taps were provided for the orifice meter to record the flow rate of air through the column The bed pressure drop was noted at two pressure taps one below the bottom of the grid and the other at the top of the column Two sets of manometers were provided for the measurement of flow rates and pressure drops one being used for the lower range and the other for the higher

While taking a run, the sample was introduced into the column and the fixed bed height was noted The movable restraint was adjusted for a particular bed expansion ratio Pressure drops across the bed and the orifice were noted as the air flow rate was increased When semi fluidization sets in, the top bed formations

* Present address Department of Chemical Engineering, Regional Engineering College Rourkela 8 Orissa India

were constantly recorded. The static and expanded bed porosities were determined in separate experiments with samples of known weight. The surface area of the particles and the shape factors were determined by the air permeability method[2].

Results and discussion

Altogether 141 sets of runs were made. Two spherical materials (mustard seed and sago of size 14/20 BSS) and four non spherical materials (table salt, sand, magnesite and ammonium sulphate of size 30/40 BSS) were studied. In addition, for table salt only, four size ranges (20/30, 30/40, 40/52 and 52/60 BSS) were examined. The lowest and highest densities of solids used were 1.12 and 2.80 g/cm³ respectively. The properties of the solid particles and the fluids used are given in detail in Table 1. Table 2 gives a typical run showing the variation of pressure drop and packed bed formation with fluid mass velocity. These effects are shown in Fig. 2. The bed expansion data for the same system are given in Table 3 and illustrated in Fig. 3.

TABLE 1

Physical properties of fluids used

Sl no	*Fluid*	*Temperature* (°C)	*Density* (g/cm³)	*Viscosity* (poise)	*Use*
1	Air at 1 atm pressure	22	0.00012	0.00018	Fluidizing medium
2	Carbon tetrachloride	22	1.583		Manometer liquid
3	Mercury	22	13.600		Manometer liquid

Physical characteristics of materials used

Sl no	*Materials used*	*Particle size* Mesh no BSS	d_p (m × 10⁴)	*Density* ρ_s (g/cm³)	*Packed bed porosity* ϵ_{pa}	*Surface area* S_v (cm²/m³)	*Sphericity* ϕ_s
Non spherical							
1	Table salt	20/30	7.51	2.100	0.596	241.0	0.331
2	Table salt	30/40	4.42	2.100	0.588	300.5	0.452
3	Table salt	40/52	3.38	2.100	0.560	302.0	0.587
4	Table salt	52/60	2.74	2.100	0.533	335.0	0.654
5	Ammonium sulphate	30/40	4.42	1.763	0.377	136.0	1.000
6	Sand	30/40	4.42	2.650	0.451	170.5	0.798
7	Magnesite	30/40	4.42	2.800	0.443	177.0	0.770
Spherical							
8	Mustard seed	14/20	11.05	1.120	0.362	54.2	1.000
9	Sago	14/20	11.05	1.304	0.380	54.2	1.000

TABLE 2

Variation of pressure drop and packed bed formation (below the top restraint) with fluid mass velocity

System salt–air, particle size 20/30 BSS, h_s 9 cm, h = 27 cm, R 3.0, t 23°C

Sl no	ΔH_1 (cm of CCl_4)	ΔP (kg/m²)	ΔH_2 (cm of)	G (kg/h m²)	h_{pa} (cm)	h_{pa}/h_s
1	1.5	23.8	3.9 CCl_4	741		
2	2.5	39.6	8.8 CCl_4	1125		
3	3.5	55.5	14.7 CCl_4	1453		
4	3.9	61.8	16.6 CCl_4	1547		
5	4.2	66.6	28.8 CCl_4	2045		
6	4.4	69.8	34.9 CCl_4	2250		
7	4.6	73.0	6.3 Hg	2840		
8	6.4	101.5	8.9 Hg	3365		
9	9.1	144.2	12.2 Hg	3950	1.5	0.166
10	17.2	272.5	24.3 Hg	5590	3.0	0.333
11	25.6	405.5	33.8 Hg	6585	4.0	0.444
12	40.6	644.0	45.1 Hg	7600	5.0	0.555

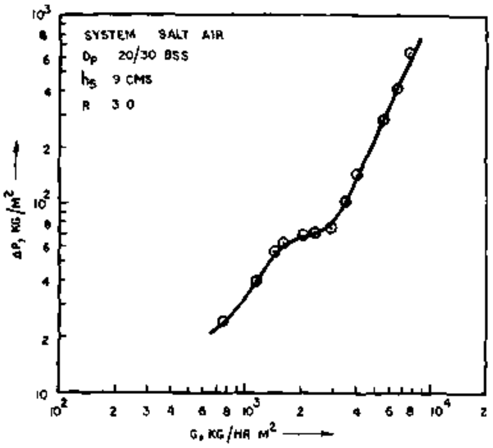

Fig 2 Variation of pressure drop with fluid mass velocity

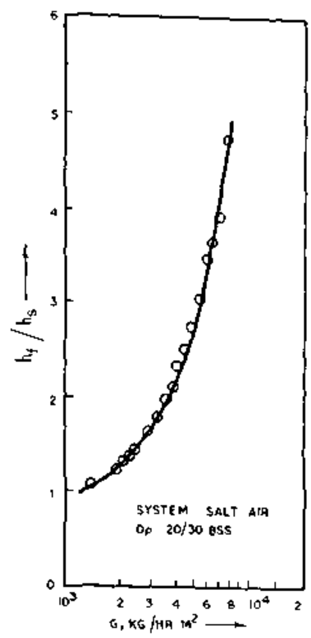

Fig 3 Variation of expanded bed height with fluid mass velocity

TABLE 3

Variation of expanded bed height and bed porosity with fluid mass velocity
System salt air, particle size 20/30 BSS, w = 64.6597 g, h_s = 4.8 cm v_s = 30.8 cm^3, ϵ_{pa} = 0.596, t 19°C

Sl no	ΔH_2 (cm of)	G (kg/h m^2)	h_f (cm)	h_f/h_s	ϵ_f
1	14.2 CCl_4	1420	5.0	1.040	0.612
2	26.4 CCl_4	1950	5.8	1.210	0.664
3	32.0 CCl_4	2152	6.2	1.290	0.688
4	37.7 CCl_4	2340	6.5	1.355	0.702
5	43.1 CCl_4	2505	6.8	1.417	0.715
6	6.7 Hg	2945	7.8	1.625	0.752
7	8.3 Hg	3270	8.4	1.750	0.770
8	10.0 Hg	3585	9.5	1.980	0.796
9	11.7 Hg	3870	10.1	2.100	0.808
10	13.2 Hg	4110	11.0	2.290	0.824
11	15.9 Hg	4530	11.9	2.480	0.837
12	19.1 Hg	4955	13.0	2.706	0.851
13	23.3 Hg	5470	14.5	3.020	0.866
14	27.3 Hg	5910	16.5	3.440	0.882
15	31.8 Hg	6390	17.3	3.600	0.888
16	38.5 Hg	7030	18.6	3.870	0.896
17	46.9 Hg	7750	22.6	4.700	0.915

Prediction of pressure drop in a semi-fluidized bed The pressure drop in a semi-fluidized bed should, ideally, be equal to the algebraic sum of the pressure drops across the fluidized section and the packed section, since they are aligned in series in the direction of flow While there is only one generalized equation[3], namely

$$\left(\frac{\Delta P}{L}\right)_f = (\rho_s - \rho_f)(1 - \epsilon_f) \tag{1}$$

for the prediction of the pressure drop across a fluidized bed, there are various correlations for the determination of the pressure drop across a packed bed A few important ones are as follows

(a) The Kozeny-Carman equation[4]
for laminar flow ($G/a\mu < 100$)

$$\left(\frac{\Delta P}{L}\right)_{pa} = \frac{5G^2 a}{g_c \rho_f \epsilon_{pa}^3}\left(\frac{G}{\mu a}\right)^{1.0} \tag{2a}$$

and for turbulent flow ($G/a\mu \gtreqless 100$)

$$\left(\frac{\Delta P}{L}\right)_{pa} = \frac{0.4 G^2 a}{g_c \rho_f \epsilon_{pa}^3}\left(\frac{G}{a\mu}\right)^{0.1} \tag{2b}$$

(b) The equation of Leva[3] and coworkers

$$\left(\frac{\Delta P}{L}\right)_{pa} = \frac{2 f G^2}{g_c \rho_f d_p}\,\frac{1}{\phi_s^{3-n}}\,\frac{(1 - \epsilon_{pa})^{3-n}}{\epsilon_{pa}^3} \tag{3}$$

where n = 1 for laminar flow, n = 2 for turbulent flow and f is the modified friction factor The values of n and f are determined from a knowledge of the state of flow and reference to the standard plot of f *versus* Re_p[4]

(c) Ergun's equation[3]

$$\left(\frac{\Delta P}{L}\right)_{pt} = 150\frac{(1-\epsilon_{pa})^2}{\epsilon_{pa}^3}\frac{\mu u}{d_p^2} + $$

$$+ 1.75\left(\frac{1-\epsilon_{pt}}{\epsilon_{pa}^3}\right)\frac{Gu}{d_p} \qquad (4)$$

Fan *et al.*[5] measured the total pressure drop occurring during semi-fluidization and compared these measured values with those calculated from correlations. They used Ergun's equation for calculation of the pressure drop for the packed section. The equation for the total pressure drop was given as

$$\Delta P_t = \left(\frac{\Delta P}{L}\right)_{pt} h_{pt} + \left(\frac{\Delta P}{L}\right)_f (h - h_{pt})$$

$$= \left[150\left(\frac{1-\epsilon_{pa}}{\epsilon_{pt}^3}\right)\frac{\mu u}{d_p^2} + 1.75\left(\frac{1-\epsilon_{pt}}{\epsilon_{pt}^3}\right)\frac{Gu}{d_p}\right] \times$$

$$\times \left[(h_1 - h)\frac{1-\epsilon_f}{\epsilon_f - \epsilon_{pa}}\right]\frac{1}{g_c} + \qquad (5)$$

$$+ \left[h_f - \frac{(1-\epsilon_{pa})(h_f - h)}{\epsilon_f - \epsilon_{pt}}\right](1 - \epsilon_f)(\rho_s - \rho_f)$$

The authors concluded that eqn. (5) gives lower values than the experimental ones.

In the present case, the packed bed pressure drop was first calculated using each of the above three equations (eqns. (2), (3) and (4)) for two systems (one spherical and one non-spherical) (see Table 4). The total pressure drop for the semi-fluidized bed was obtained in each case by adding the packed bed pressure drop to the fluidized bed pressure drop obtained from eqn. (1), and these values were then compared with the experimental values (Table 5). It was found that use of the Kozeny–Carman equation gave much lower values in all cases, whereas the equation suggested by Leva gave a few values higher than the experimental ones and the rest lower. The values of pressure drops as calculated by Ergun's equation were found to be on the lower side. In further work Ergun's equation only was used for the calculation of the packed bed pressure drop. The use of Leva's equation, although justified to some extent (because of its closeness to the experimental values in some cases), was not favoured since it involves quantities like the modified friction factor f and the state of flow factor n which must be taken from charts. It is difficult to read the exact values of these quantities and any error here would manifest itself in the form of wide deviations. In addition, Leva has suggested different equations for the packed bed pressure drop taking into account the effect of surface roughness (a quantity that cannot be measured directly)[3]. In contrast, Ergun's equation is quite simple as it involves quantities which are directly measurable.

Development of the correlation. As has been reported earlier[6] and has also been observed in the present case, the porosity of the packed section causes difficulty in the calculation of the over-all pressure drop in the semi-fluidized bed. Available equations for packed bed pressure drops are quite sensitive to bed porosity variations. Also, there is no direct way of simultaneously measuring the porosities of the fixed

TABLE 4

Comparison of packed bed pressure drops

Spherical system: mustard seed–air, d_p = 0.001105 m				*Non-spherical system: salt–air, d_p = 0.000442 m*			
	Pressure drop (kg/m²)				*Pressure drop* (kg/m²)		
Sl. no.	*by Kozeny–Carman eqn.*	*by Leva's eqn.*	*by Ergun's eqn.*	*Sl. no.*	*by Kozeny–Carman eqn.*	*by Leva's eqn.*	*by Ergun's eqn.*
1	2.12	7.34	6.42	1	1.63	9.35	2.01
2	11.90	22.80	21.40	2	14.75	91.00	21.90
3	35.80	97.40	85.50	3	32.70	208.00	54.50
4	60.30	155.20	135.00	4	36.80	205.50	57.60
5	69.20	159.00	139.20	5	40.50	242.00	55.00
6	146.50	385.00	336.50	6	54.20	350.00	82.90
				7	60.90	360.00	88.00
				8	81.10	517.00	133.50
				9	83.90	568.00	157.50
				10	97.00	618.00	156.30
				11	105.40	719.00	188.60
				12	116.50	783.00	206.00
				13	120.00	793.00	204.00

TABLE 5

Total pressure drop of semi fluidized bed

Sl no	by Kozeny Carman eqn	by Leva's eqn	by Ergun's eqn	Experimental
Non spherical particles–system salt air d_p 0.000442 m				
1	84.60	92.30	85.01	169.6
2	91.85	168.10	99.00	242.5
3	97.20	272.50	119.00	323.0
4	97.70	266.40	118.50	347.0
5	94.40	295.90	108.90	250.5
6	106.70	402.50	135.40	330.0
7	103.40	402.50	130.50	323.0
8	119.90	555.80	172.30	461.0
9	131.00	615.10	198.60	531.0
10	126.20	647.20	185.50	555.0
11	144.60	758.20	227.80	548.5
12	147.10	813.60	236.60	645.0
13	144.40	817.40	228.40	670.0
Spherical particles system mustard seed air d_p 0.001105 m				
1	58.12	73.30	62.40	331.5
2	65.30	76.20	74.80	198.0
3	87.50	149.10	137.20	366.0
4	107.40	202.20	182.00	398.0
5	110.40	200.20	180.40	314.0
6	175.30	413.80	365.30	469.0

and the fluidized sections of the semi-fluidized bed. This results in a wide variation between the experimental and calculated values of the pressure drops in the bed. Hence an attempt has been made in the present work to give a correction factor in terms of system variables, which can be used for the prediction of the pressure drop in the semi fluidized bed.

The pressure drop expression can now be written as

$$(\Delta P_t)_{expt} = C(\Delta P_t)_{cal} \tag{6}$$

where $(\Delta P_t)_{expt}$ is the experimental value of the total pressure drop, $(\Delta P_t)_{cal}$ is the calculated value of the total pressure drop and C is the correction factor. Rearranging, we get

$$\frac{(\Delta P_t)_{expt}}{(\Delta P_t)_{cal}} = C \tag{7}$$

It is imperative that the correction factor should be related to the system parameters. The parameters of importance in this case are

$$\frac{D_c}{d_p}, \quad \frac{\rho_s}{\rho_f}, \quad \frac{h_s}{D_c}, \quad R \quad \text{and} \quad \frac{h_{p1}}{h_s}$$

The relation can be written in the following manner

$$C = \psi\left[\frac{D_c}{d_p}, \quad \frac{\rho_s}{\rho_f}, \quad \frac{h_s}{D_c}, \quad R \quad \frac{h_{p1}}{h_s}\right] \tag{8}$$

or

$$C = A\left(\frac{D_c}{d_p}\right)^{a_1}\left(\frac{\rho_s}{\rho_f}\right)^{a_2}\left(\frac{h_s}{D_c}\right)^{a_3}(R)^{a_4}\left(\frac{h_{p1}}{h_s}\right)^{a_5} \tag{9}$$

where A is a constant and a_1, a_2, a_3, a_4 and a_5 are exponents of the system variables.

The exponents of eqn (9) have been evaluated by plotting the correction factor against each of the system variables on log log paper. After substitution of these exponents, eqn (9) becomes

$$C = A\left(\frac{D_c}{d_p}\right)^{0.415}\left(\frac{\rho_s}{\rho_f}\right)^{0.935}\left(\frac{h_s}{D_c}\right)^{1.614}(R)^{1.23} \times$$

$$\times\left(\frac{h_{p1}}{h_s}\right)^{0.504} \tag{10}$$

where A is the coefficient of the over all product. If B is the exponent of the over-all product (prod.) which is the correlation factor for the exponents of the system variables, the equation

$$C = A\,(\text{prod.})^B \tag{11}$$

is valid.

The correction factor has been plotted on log log paper (Fig. 4) against the product

$$\left(\frac{D_c}{d_p}\right)^{0.415}\left(\frac{\rho_s}{\rho_f}\right)^{0.935}\left(\frac{h_s}{D_c}\right)^{1.614}(R)^{1.23}\left(\frac{h_{p1}}{h_s}\right)$$

Two different straight lines with slopes of 0.583 and 1.268 were obtained for spherical and non spherical particles respectively. The data with asterisks represent conditions of simultaneous variation of a number of variables. In all other cases one parameter was changed at a time, the remainder being kept constant. The equations for the two lines can be written as follows.

For non-spherical particles

$$C = \frac{(\Delta P_t)_{actual}}{(\Delta P_t)_{calc}}$$

$$= 1.95 \times 10^{-1}\left[\left(\frac{D_c}{d_p}\right)^{0.24}\left(\frac{\rho_s}{\rho_f}\right)^{0.55}\left(\frac{h_s}{D_c}\right)^{0.94} \times\right.$$

$$\left.\times (R)^{0.72}\left(\frac{h_{p1}}{h_s}\right)^{0.29}\right] \tag{12}$$

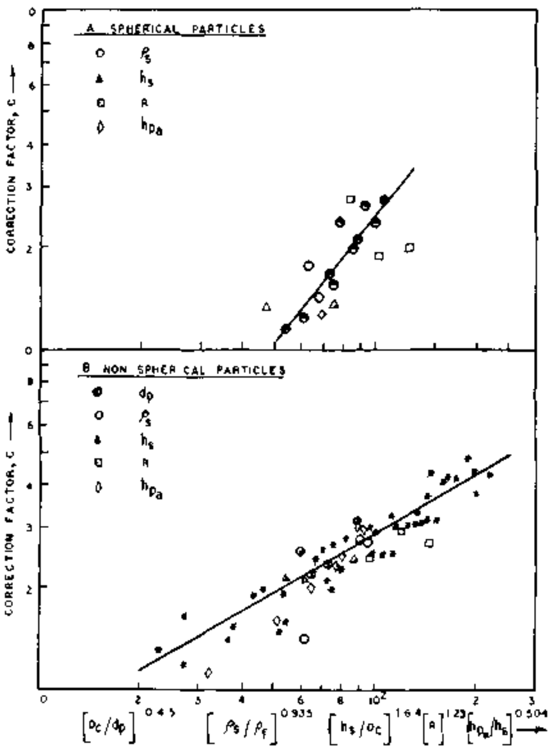

Fig. 4 Relation of C with the system variables

For spherical particles

$$C = \frac{(\Delta P_t)_{actual}}{(\Delta P_t)_{calc}}$$

$$= 7.3 \times 10^{-3}\left[\left(\frac{D_c}{d_p}\right)^{-0.53}\left(\frac{\rho_s}{\rho_f}\right)^{1.18}\left(\frac{h_s}{D_c}\right)^{2.05} \times (R)^{1.56}\left(\frac{h_{pa}}{h_s}\right)^{0.64}\right] \quad (13)$$

The values of the pressure drop calculated by using the above correction factor have been found to be in good agreement with the experimental data. In the case of non spherical particles most of the data lie within ± 15% the maximum deviation being of the order of 35–40% (for a few cases only). All the system variables have been exhaustively examined. However the correlation for spherical particles has limitations in that only two materials have been studied. The maximum deviation in this case is as high as 50–60%. It is therefore suggested that further investigations with spherical particles should be carried out.

Nomenclature

A	constant of equation
a	specific surface of the bed L^2/L^3
B	exponent
C	Pressure drop correction factor
D_c	diameter of column, L
d_p	particle diameter, L
f	modified friction factor
g_c	gravitational constant, $L\theta^{-2}$
G	mass velocity of fluid $L\theta^{-1}L^{-2}$
ΔH_1	pressure drop across the bed, L
ΔH_2	pressure drop across the orifice meter, L
h	over-all height of the column (or semi-fluidized bed) L
h_s	height of the initial static bed, L
h_{pa}	height of the packed section in the semi fluidized bed, L
h_f	height of the fully fluidized bed L
n	state of flow factor
$(\Delta P/L)_f$	pressure gradient across a fluidized bed FL^{-3}
$(\Delta P/L)_{pa}$	pressure gradient across a packed bed, FL^{-3}
ΔP_t	over-all pressure drop across the semi fluidized bed FL^{-2}
R	bed expansion ratio in semi-fluidization dimensionless
S_v	surface area of particle per unit volume of solid L^2/L^3
u	linear velocity of fluid $L\theta^{-1}$
w	total weight of solid in the column M

Greek symbols

Δ	finite change of variable
ψ	function
ϕ_s	sphericity of particles
μ	viscosity $ML^{-1}\theta^{-1}$
ρ	density ML^{-3}
ϵ	bed porosity

Subscripts

c	column
f	fluid or fluidized bed
pa	packed bed
s	solid or static bed

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Relation Between Maximum Semi-Fluidization and Minimum Fluidization Velocity in Liquid-Solid Systems

G K Roy, *Associate Member*

Dr K J R Sarma, *Non-member*

In this paper data on semi-fluidization characteristics of some liquid-solid systems have been reported. Also, a correlation relating the maximum semi-fluidization with the minimum fluidization velocity in terms of various systems parameters has been developed and discussed.

NOTATIONS

A = constant or coefficient

D_c = diameter of column (semifluidizer), L

d_p = particle diameter, L

G = mass velocity of fluid, $M\theta^{-1}L^{-2}$

G_{mf}, G_{msf} = mass velocity for minimum fluidization and maximum semi-fluidization conditions respectively, $M\theta^{-1}L^{-2}$

h = overall height of column (semifluidized bed) L

h_s = height of initial static bed, L

R = bed expansion ratio in semi-fluidization, h/h_s

Ψ = function

μ = viscosity of fluid, $M\theta^{-1}L^{-1}$

ρ_f, ρ_s = density of fluid and solid respectively, ML^{-3}

INTRODUCTION

The various aspects of liquid-solid semi-fluidization which have been studied and reported earlier by the authors, include the prediction of minimum and maximum semi-fluidization velocities[2], packed bed formation. In a recent paper[3] the authors have given a correlation for the prediction of minimum semi-fluidization velocity from minimum fluidization velocity. An attempt has been made here to develop a correlation which relates the ratio of the maximum semi-fluidization velocity to the minimum fluidization velocity with the system parameters.

EXPERIMENTAL SET-UP

The experimental set-up used in the present study is given in Fig 1. The details of the set-up and the method of investigations are described in an earlier paper[2].

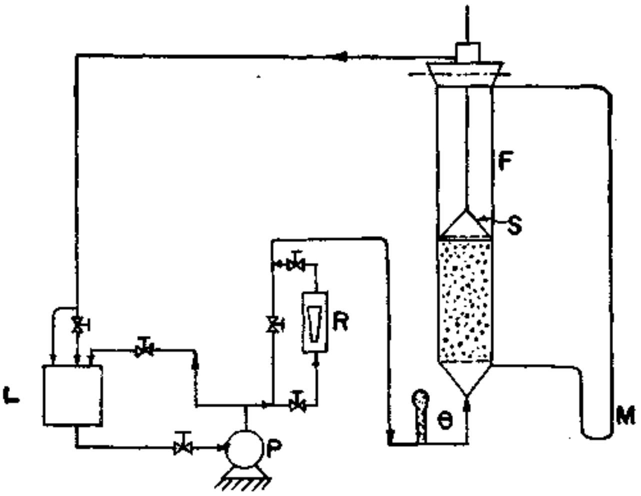

Fig 1 Liquid-solid semi-fluidization set-up
L = Liquid Reservoir
P = Pump
R = Rotameter
θ = Thermometer
F = Fluidization column
S = Adjustable Restraint (with screen)
M = Monometer

RESULTS

The onset of fluidization and maximum semi-fluidization conditions are the two extreme operations of the semi-fluidization phenomena. While the former corresponds to the initiation of particle movement in a fluid-solid bed, the latter indicates the fluid velocity at which all the solids are transferred to the packed section below the top restraint and there is no particle movement in the bed. There are a few correlations for the prediction of minimum fluidization velocity from a knowledge of the fluid and solid properties. Hence the ratio of maximum semi-fluidization to the minimum fluidization velocity can be related to the various parameters of the system.

The onset of fluidization velocity can be calculated from Leva's simplified equation[1]. (FPS units)

$$G_{mf} = 688\, d_p^{\,1.82} \frac{[\rho_f(\rho_s - \rho_f)]^{0.94}}{\mu^{0.88}} \qquad (1)$$

G K Roy and Dr K J R Sarma are with the Department of Chemical Engineering, Regional Engineering College, Rourkela.
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As equation (1) is valid for $Re_{mf} < 10$, for higher values correction factors were applied to obtain the accurate values of G_{mf}. The values calculated by the above equation are given in Table 1.

TABLE 1 COMPARISON OF MAXIMUM-FLUIDIZATION VELOCITY

SYSTEM	$\frac{D_c}{d_p}$	$\frac{\rho_s}{\rho_f}$	G_{mf} $\frac{\text{lbs}}{\text{hr ft}^2}$	G_{msf} $\frac{\text{lbs}}{\text{hr ft}^2}$ CAL	G_{msf} $\frac{\text{lbs}}{\text{hr ft}^2}$ EXPT	PERCENTAGE DEVIATION
Dolomite-water	16.45	2.76	20 600	194 000	180 000	+ 7.57
Dolomite-water	36.40	2.76	9 440	124 000	115 000	+ 7.82
Stonechips-water	16.45	2.65	19 800	191 000	180 000	+ 6.11
Stonechips-water	36.40	2.65	9 100	123 000	110 000	+11.80
Iron ore-water	16.45	5.05	33 800	211 500	260 000	—18.65
Iron ore-water	36.40	5.05	17 200	151 500	175 000	—13.40
Coal water	36.40	1.58	3 970	75 500	84 000	—10.10

DEVELOPMENT OF CORRELATION

In fluidization as well as semi-fluidization, properties of the fluid and the solid as well as the geometry of the system will determine the various sequences of the phenomena. Among the variables, important ones are: h_s, D_c, d_p, ρ_s, ρ_f and R. During investigations it was observed that the bed expansion ratio and the initial static bed height have no influence on the maximum semi-fluidization velocity. Writing the other variables in the form of dimensionless groups

$$\frac{G_{msf}}{G_{mf}} = \Psi \left(\frac{D_c}{d_p}, \frac{\rho_s}{\rho_f} \right) \qquad (2)$$

or

$$\frac{G_{msf}}{G_{mf}} = A \left(\frac{D_c}{d_p} \right)^{a_1} \left(\frac{\rho_s}{\rho_f} \right)^{a_2} \qquad (3)$$

where A is a constant and a_1 and a_2 are the respective exponents of the system variables.

The effects of the individual parameters have been studied and the exponents evaluated. Substituting these exponents, equation (3) becomes

$$\frac{G_{msf}}{G_{mf}} = A \left[\left(\frac{D_c}{d_p} \right)^{0.42} \left(\frac{\rho_s}{\rho_f} \right)^{-0.67} \right]^B \qquad (4)$$

where, A is the coefficient and B is the exponent of the overall product which is the correlation factor for the exponents of the system variables.

The equation for the straight line (Fig 2) is

$$\frac{G_{msf}}{G_{mf}} = 5{\cdot}71 \left(\frac{D_c}{d_p} \right)^{0{\cdot}42} \left(\frac{\rho_s}{\rho_f} \right)^{-0{\cdot}67} \qquad (5)$$

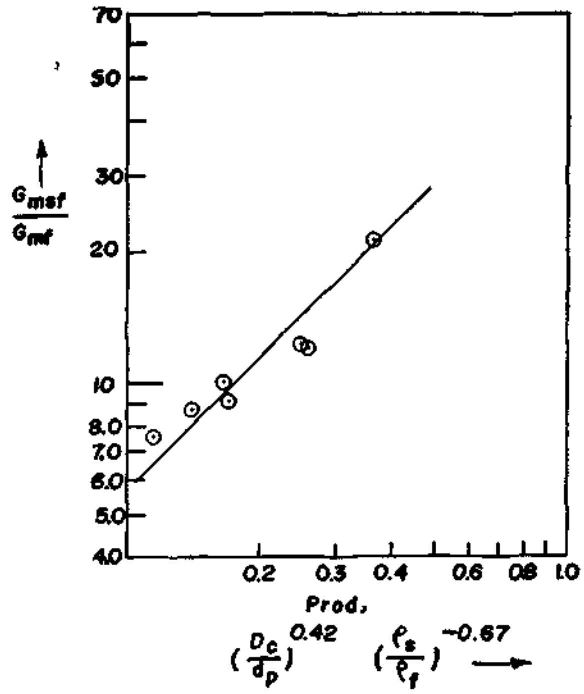

Fig 2 Gmsf/Gmf with system variation

The values of G_{msf} calculated from the above equation have been found to be in good agreement with the experimental data. The individual deviations are given in Table 1. It is found that, except for one case, the deviations lie within $\pm 15\%$.

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